U.S. 101 MP 103.65 Unnamed Tributary to Big Creek (WDFW ID 991501): Preliminary Hydraulic Design Report

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Contents

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Deleted: 33
Deleted: 33
Deleted: 55
Deleted: 88
Deleted: 88
Deleted: 88
Deleted: 99
Deleted: 99
Deleted: 1010
Deleted: 1010
Deleted: 1617
Deleted: 1818
Deleted: 1818
Deleted: 1819
Deleted: 2122
Deleted: 2223
Deleted: 2728
Deleted: 2728
Deleted: 2930
Deleted: 3233
Deleted: 3233
Deleted: 3233
Deleted: 3233
Deleted: 3435
Deleted: 3637
Deleted: 4042
Deleted: 4143
Deleted: 4244
Deleted: 4648

Figures

Deleted: 38
Deleted: 39
Deleted: 39
Deleted: 40
Deleted: 40
Deleted: 42
Deleted: 43
Deleted: 43
Deleted: 45
Deleted: 45
Deleted: 46
Deleted: 48
Deleted: 48
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Deleted: 49
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Deleted: 51
Deleted: 53
Deleted: 56
Deleted: 57
Deleted: 57
Deleted: 58
Deleted: 65
Deleted: 66
Deleted: 67
Deleted: 69

Deleted: Figure 1: Vicinity map 2¶
Figure 2: NLCD 2016 land cover map 4¶
Figure 3: 1990 aerial photograph showing extensive clearcutting in the project stream's basin 4¶
Figure 4: Geologic map of project stream basin area 6¶
Figure 5: Additional Geologic Features and LiDAR Digital Elevation Model (DEM) mapped at 1:18000 scale with stationing in feet 7¶
Figure 6: Culvert inlets 11¶
Figure 7: Culvert outlets 12¶
Figure 8: Representative views of the channel upstream of US 101 12¶
Figure 9: Representative streambed material upstream of culverts 13¶
Figure 10: Start of entrenched reach upstream of surveyed reach 13¶
Figure 11: Log weir 14¶
Figure 12: ELJ 1 15¶
Figure 13: ELJ 2 15¶
Figure 14: ELJ 3 16¶
Figure 15: representative LWM downstream of culverts 16¶
Figure 16: Representative view of extensive gravel deposits in downstream reach 17¶
Figure 17: Reference reach and locations of BFW measurements and substrate sampling 20¶
Figure 18: Representative bankfull width measurements in non-incised reach upstream of culverts 21¶
... [1]

Tables

Deleted: 3
Deleted: 9
Deleted: 20
Deleted: 22
Deleted: 30
Deleted: 30
Deleted: 34
Deleted: 43
Deleted: 44
Deleted: 47
Deleted: 50
Deleted: 55
Deleted: 56
Deleted: 60
Deleted: 63
Deleted: 71

Deleted: Table 1: Land cover table 3¶
Table 2: Native fish species potentially present within the project area 9¶
Table 3: Bankfull width measurements 20¶
Table 4: Sediment properties in vicinity of project crossing 23¶
Table 5: USGS regression-based estimates of peak flow 31¶
Table 6: Local USGS Gages Used to Evaluate Bias in USGS Regression Predictions 31¶
Table 7: Manning's n hydraulic roughness coefficient values used in the SRH-2D model 35¶
Table 8: Hydraulic results for existing conditions within the main channel 46¶
Table 9: Existing-conditions velocities including floodplains at select cross sections 46¶
Table 10: Hydraulic results for natural conditions within the main channel 49¶
Table 11: Natural conditions velocities including floodplains at select cross sections 49¶
Table 12: Flood-prone widths and floodplain utilization ratio results 52¶
Table 13: Hydraulic results for proposed conditions within the main channel 57¶
Table 14: Proposed conditions velocity predictions at select cross sections 58¶
Table 15: Velocity comparison for 20-foot structure 62¶
Table 16: Parameters relevant to freeboard specification for proposed replacement structure 62¶
Table 17: Comparison of observed and proposed streambed material 64¶
Table 18: Report summary 72¶

1 Introduction

To comply with United States et al. vs. Washington et al. No. C70-9213 Subproceeding No. 01-1 dated March 29, 2013 (a federal permanent injunction requiring the State of Washington to correct fish barriers in Water Resource Inventory Areas [WRIAs] 1–23), the Washington State Department of Transportation (WSDOT) is proposing a project to provide fish passage at the United States Highway 101 (U.S. 101) crossing of the unnamed tributary (UNT) to Big Creek at Mile Post (MP) 103.65. This existing structure on U.S. 101 has been identified as a fish barrier by the Washington Department of Fish and Wildlife (WDFW) and WSDOT Environmental Services Office (ESO) (site identifier [ID] 991501) and has an estimated 11,266 linear feet (LF) of habitat gain.

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Per the injunction, and in order of preference, fish passage should be achieved by (1) avoiding the necessity for the roadway to cross the stream, (2) use of a full-span bridge, or (3) use of the stream simulation methodology. Avoidance of the stream crossing was determined not to be viable given the location of the highway and the need to maintain this critical transportation corridor. The stream simulation approach was followed for this site based on site characteristics.

The crossing is located in Grays Harbor County 5.6 miles southeast of Humptulips, Washington, in WRIA 22. The highway runs in an east–west direction at this location and is about 3,600 feet (ft) from the confluence with Big Creek. The project stream generally flows from north to south beginning approximately two miles upstream of the U.S. 101 crossing (Figure 1).

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The proposed project will replace two existing 66-inch (in) diameter round corrugated metal pipe (CMP) culverts, each approximately 111 feet long, with a structure designed with a minimum hydraulic opening of 24 feet, which includes accommodation for wildlife. A specific structure type is not recommended in this Preliminary Hydraulic Design (PHD) Report. The floodplain utilization ratio computed for this site results in its being classified a confined channel, and thus the proposed structure is designed to meet the requirements of the federal injunction using stream simulation design criteria as described in the 2013 WDFW *Water Crossing Design Guidelines* (WCDG) (Barnard et al. 2013). This design also follows the WSDOT *Hydraulics Manual* (WSDOT 2019) with supplemental analyses as noted.

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A draft PHD report was prepared in 2020 by WSDOT and HDR Engineering, Inc. under Agreement Number Y-12374 between HDR and WSDOT Environmental Services Office. WSDOT received review comments on the draft PHD report from WDFW and the Quinault Indian Nation (QIN). As part of Kiewit's Coastal-29 Team of the US 101/SR 109 Grays Harbor/Jefferson/Clallam, Remove Fish Barriers Project under a Progressive Design-Build (PDB) contract between Kiewit and WSDOT, Kleinschmidt Associates (KA) reviewed the draft PHD report, updated the hydraulic modeling and design, addressed WDFW and Tribe comments, and prepared this Draft Final PHD report using material in the draft PHD report as a starting point. Responses to WDFW and Tribe comments are included in Appendix J. While HDR's original field observations and measurements, and selected figures have been retained in this report, all writing and analyses in the draft PHD report have been reviewed, edited, and updated where determined necessary.

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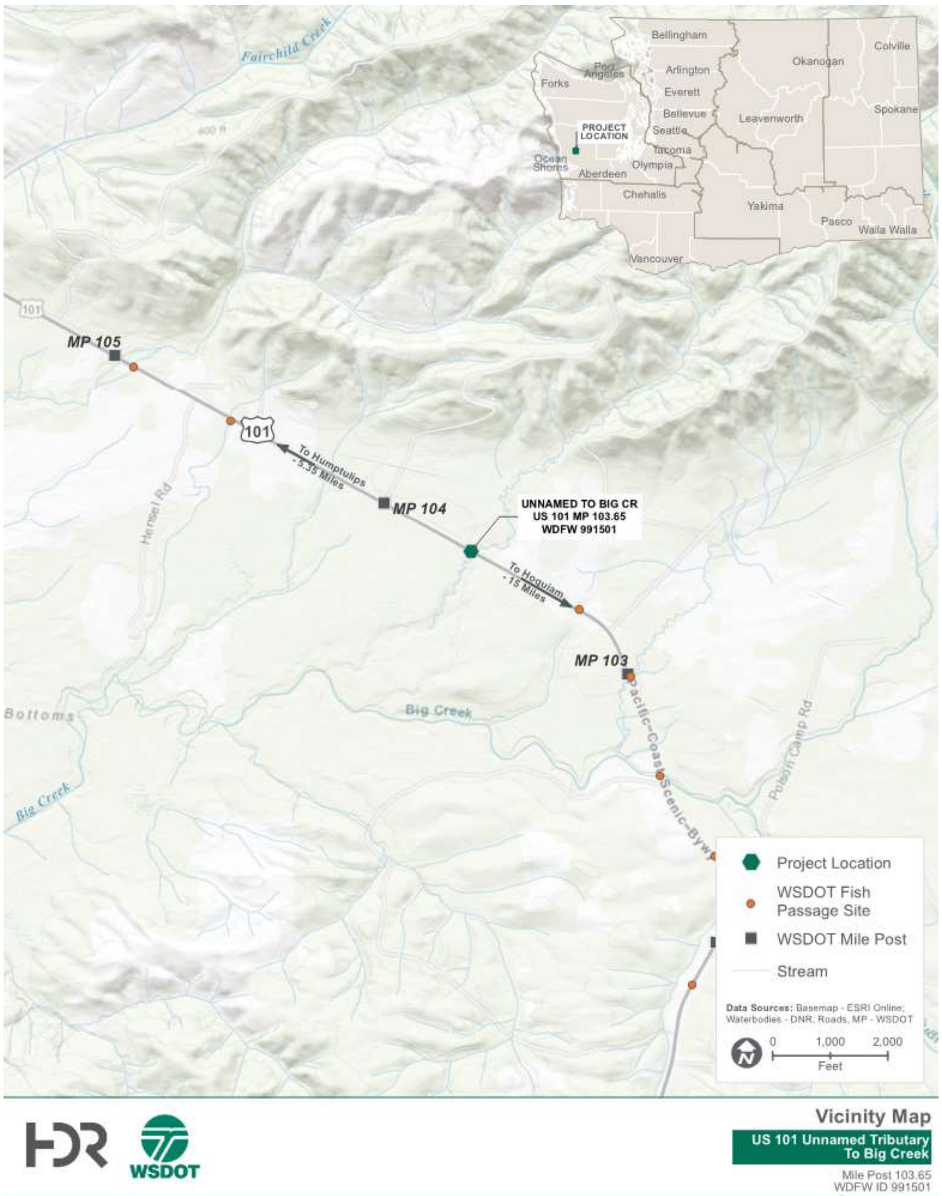

Figure 1: Vicinity map

2 Watershed and Site Assessment

The existing site was assessed in terms of watershed, land cover, geology, floodplains, fish presence, observations, wildlife, and geomorphology. This performed using desktop research including aerial photos; resources such as the United States Geological Survey (USGS), Federal Emergency Management Agency (FEMA), and WDFW; and past records like observation, maintenance, and fish passage evaluation; and site visits.

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2.1 Watershed and Land Cover

The project stream flows in a generally southwesterly direction and joins Big Creek approximately 3,600 feet downstream of the U.S. 101 culvert. Big Creek drains to the Humptulips River, which flows southerly to Grays Harbor and eventually into the Pacific Ocean. The project stream's watershed is generally forested and actively managed for timber harvest, with drainage intersected by the U.S. 101 crossing and a network of forest roads. According to US Geological Survey's StreamStats website, the basin has a mean slope of 21 percent, a total basin relief of 520 feet, and less than 18 percent of slopes greater than 30 percent (USGS 2021). The 2016 National Land Cover Database (NLCD) map shows land cover at that time to consist primarily of evergreen forest (Figure 2; Table 1). There has since been a recent clearcut harvest on the north side of the channel downstream of US 101. The Grays Harbor County Assessor's Office web mapping database indicates the stream flows through various parcels owned by timber companies and Grays Harbor County. Historical aerial photographs show timber harvest has occurred as a patchwork of clearcuts across the basin over time. Prior to 2005 and the implementation of Washington's Forest Practices Habitat Conservation Plan, timber harvest occurred without leaving a riparian management zone (Figure 3).

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Table 1: Land cover table

Land cover class	Basin coverage (percent)
Evergreen forest	86.8
Developed	4.0
Shrub/scrub	3.7
Mixed forest	3.1
Deciduous forest	2.4

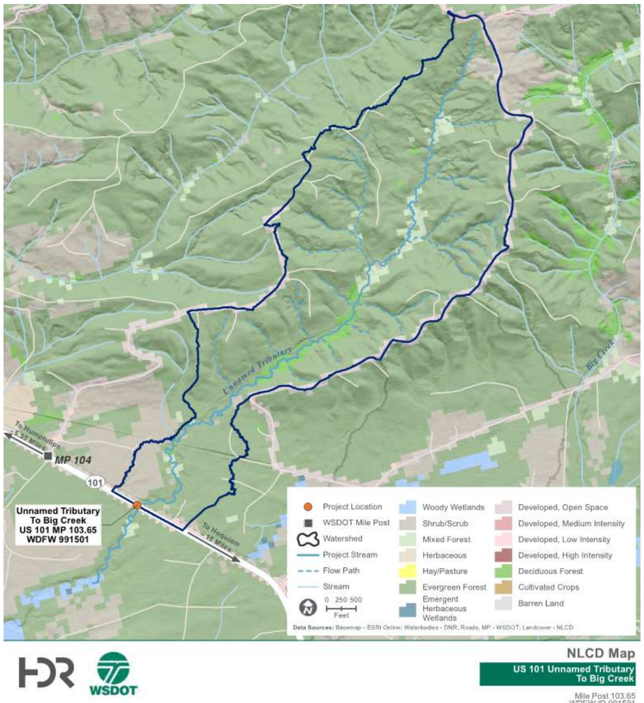

Figure 2: NLCD 2016 land cover map

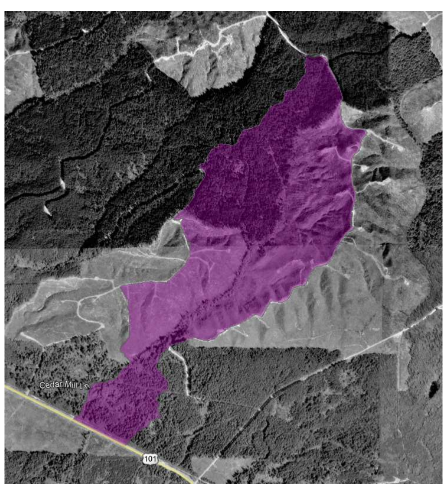

Figure 3: 1990 aerial photograph showing extensive clearcutting in the project stream's basin

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2.2 Geology and Soils

The project stream flows through a tectonically active area with mapped Quaternary faults. A geologic map prepared at the 1:100,000 scale shows the upper reach of the basin is part of the uplifted Humptulips Formation unit (Em(2ht)), which consists of Eocene-age marine sedimentary rocks (Figure 4; Logan, 2003; obtained from WDNR (2016). In contrast, the lower elevation quarter of the watershed lies within a Pleistocene alpine glacial outwash unit (Qapo) that occupies a structural trough and includes silt, sand, and gravel that is commonly iron-oxide stained and that was deposited in streambeds and fans (Logan 2003). The unit includes low-terrace surfaces that are commonly dissected. No detailed geological maps (1:24,000 scale) have been published for this region.

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Logan's mapping was completed before the availability of light detecting and ranging (LiDAR) data for this region. Two smaller scale geological features are evident in a LiDAR DEM viewed at 1:18,000 scale: a relict alluvial fan largely upstream of US 101, and the Big Creek's inset valley to the south (Figure 5). Prior to the Holocene period, the project stream deposited a broad alluvial fan (estimated to be approximately 4000 feet wide and 50 feet thick) on the north side of the outwash trough. During the Holocene period, the project stream channel and an approximately 85-250 feet wide floodplain appear to have incised within this alluvial fan. Throughout the ensuing Quaternary period, Big Creek reworked the southern portion of the outwash trough creating an alluvial valley (1200 feet wide) that appears to have incised 20-50 feet below the surrounding outwash deposits. As a result, terraces formed on the northside of the Big Creek Valley. The tributaries flowing north to south across the outwash have had a range of success eroding the terraces to establish a new equilibrium to the lower baseline. The longitudinal elevation profile suggests that the project stream has adjusted to the Big Creek base level control, and eroded the terrace with a notable knickpoint propagating upstream (See section 2.8).

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While the channel bed downstream of the crossing is composed of extensive gravel deposits, field observations of materials in and around the channel indicate the presence of key controls on vertical channel stability. In addition to the gravel, silt, and sand that would be expected to dominate the channel based on the basin-scale geology, there are local expressions of indurated gravelly conglomerate and cohesive silt in the channel bed and banks. Upstream of the US 101 crossing, the channel bed is composed of gravel and streambanks are composed of non-cohesive, silty sand and gravel. Downstream, the streambanks in the vicinity of an engineered log weir are non-cohesive. Farther downstream of the weir, the streambanks include sections with cohesive silt in the channel bed and toe of the banks, with alluvium above. Between Station 3260 and 3100 in Figure 5, we observed this unit of weathered cohesive silts and clay, with ancient buried logs exposed on the banks and in scour holes within the channel. Farther downstream, there is a grade control within the channel bed that is formed by a sill of an indurated matrix-supported conglomerate.

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A previous geotechnical boring at the crossing found 10 feet of brown well-graded gravel with wood underneath 15 feet of road fill (WSDOT 2020). Below that, the strata are thinner, change in color to gray and include more silt, and are representative of the mapped Pleistocene Glacial outwash. There are two thin strata logged as Sandy Elastic silt within the first 20 feet of the contact, but the units do not align horizontally with exposed cohesive silt banks downstream. The glacial outwash sediments deposits can be highly weathered and include thin, discontinuous layers of silt, clays and wood, and form where there was significant off-channel deposition of stagnant floodwaters (Logan 2003; Thackray 2008).

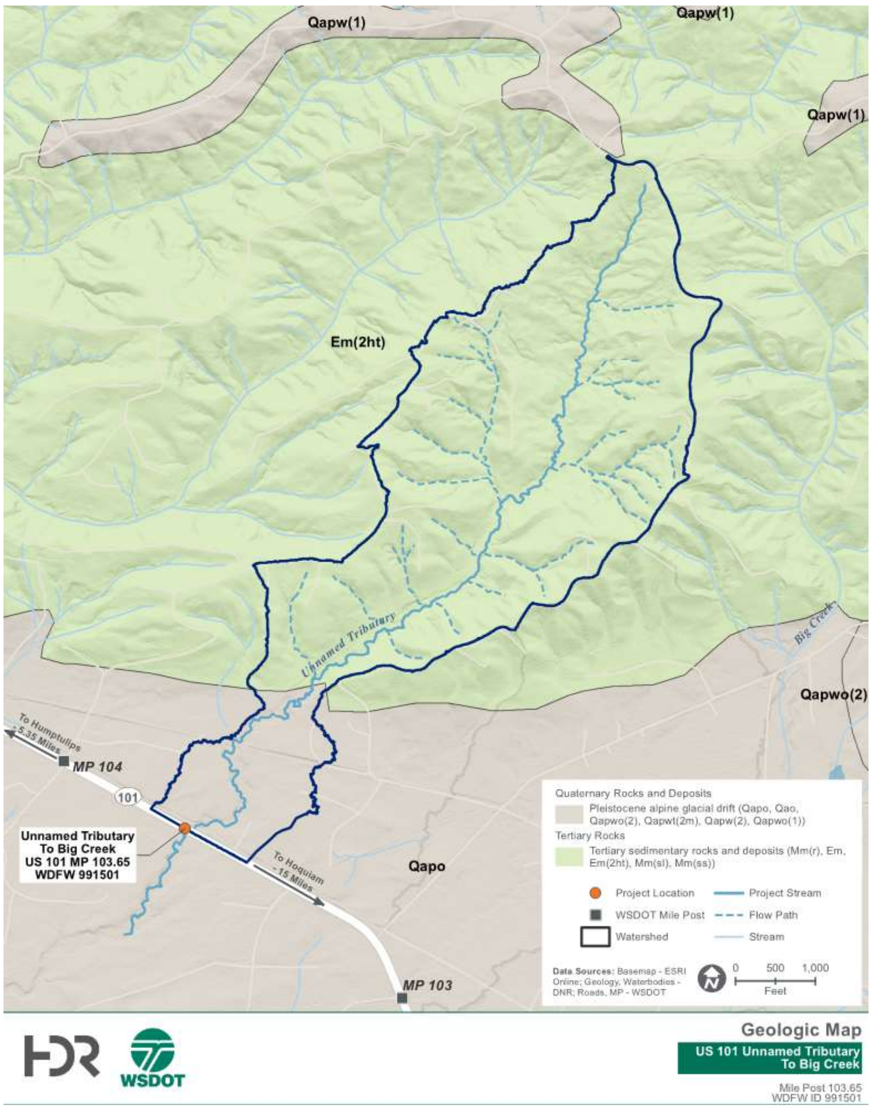

Figure 4: Geologic map of project stream basin area

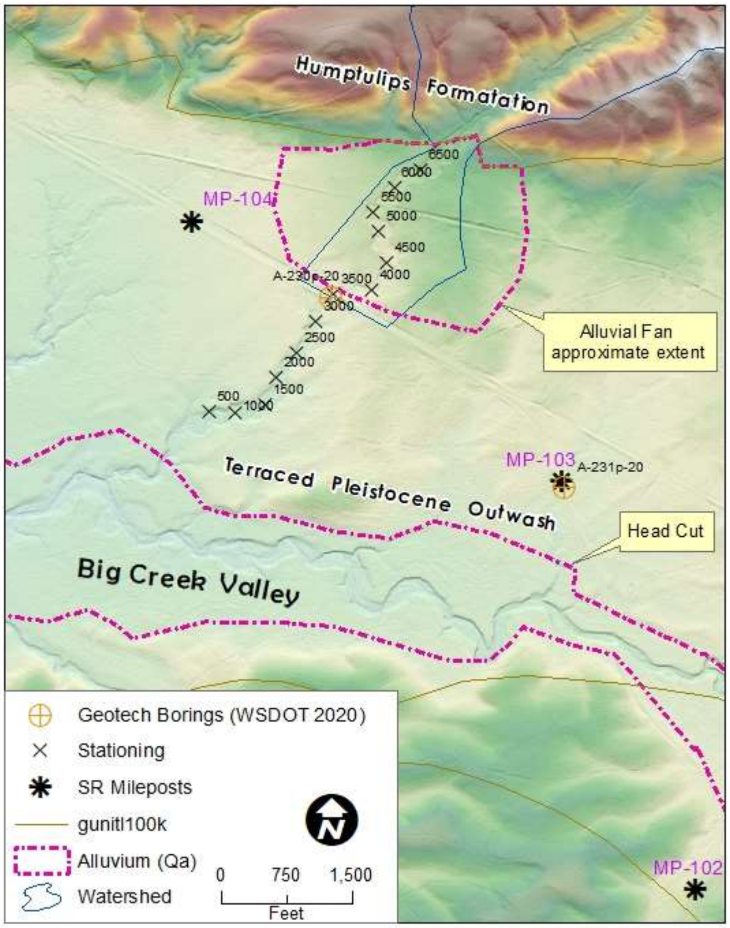

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Figure 5: Additional geologic features and LiDAR Digital Elevation Model (DEM) mapped at 1:18000 scale with stationing in feet

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Our interpretation is that the project site is located on the distal end of a relict alluvial fan built out onto a weathered Pleistocene glacial outwash deposit. During a July 2021 field visit (see Appendix B), the erodible banks upstream of the crossing were noted to be composed of alluvium, sometimes underlain by weathered gravelly outwash. Downstream the surficial layer of the alluvial fan appeared to thin. As the project stream scours alluvial soils, it can unearth fine-grained cohesive layers within this Pleistocene outwash. These cohesive layers are likely discontinuous and sandwiched between non-cohesive sediments.

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No indicators of landslide activity were observed during field visits. A boundary search conducted on 8/2021 of the DNR landslide inventories and hazards identified no landslide studies or landslide hazards within the watershed (WDNR 2020a, 2020b). The watershed’s hillslopes are composed almost exclusively of Copalis and Le Bar soil types, which consist of moderately to highly erodible Hoquiam, Lytell, and Wishkah silt loams (NRCS 2021).

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2.3 Floodplains

The project is not within a regulatory Special Flood Hazard Area, which is the 1 percent or greater annual chance of flooding in any given year. The existing U.S. 101 culvert is located in Zone X (unshaded) based on the FEMA Flood Insurance Rate Map (FIRM) 53027C0470D effective February 3, 2017 (see Appendix A). An unshaded Zone X represents areas of minimal flood hazard from the principal source of flooding in the area (Big Creek) and is determined to be outside the 0.2 percent annual chance floodplain. The mapped regulatory floodplain for Big Creek begins approximately 400 feet downstream of the crossing. Channel grading is not anticipated to occur within the mapped regulatory floodplain zone.

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2.4 Site Description

There are two parallel culverts at the site that were documented to have an overall estimated 67 percent passability rating because of a water surface drop and high velocities at the upstream ends (WDFW 2019a). The culverts are downstream of an estimated 11,266 LF of habitat. Numerous young of year Coho Salmon (*Oncorhynchus kisutch*) were observed upstream of the culverts in the spring of 2021, however, in what appeared to be comparable densities as downstream, indicating that the culverts may not be substantially impeding passage to spawning habitat upstream.

Fish passage conditions were first improved by WDFW at the site via a project constructed in 1997; the design plans were provided to WSDOT in 2021. A log weir streambed grade control structure was installed into the streambanks with stabilizing rock approximately 30 feet downstream of the culvert outlets, with a water surface drop of approximately 1.7 feet. A 67-foot-long culvert under an old railroad grade that ran parallel to and upstream of the U.S. 101 crossing was removed, and an approximately 100 feet length of the grade was also removed to restore an open channel.

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The log control structure was later identified as a fish barrier and repaired in 2003. At that time three engineered log jams (ELJ) were placed in the channel just downstream of the log control structure. These four structures are still in place, but with evidence of significant channel incision since construction (see Section 2.8). At a 2005 field visit, WDFW identified a 40-foot-long section in the upper ends of both culverts with velocity around 4 ft/s (WDFW 2019a).

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The two culverts have not been identified as failing or with a status of chronic environmental deficiency, and no maintenance problems have been noted by WSDOT.

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2.5 Fish Presence in the Project Area

The project stream is a right bank tributary to Big Creek, which then flows into the Humptulips River. Table 2 provides a list of fish species that may be affected by the culvert crossing. WDFW SalmonScape and Priority Habitats and Species (PHS) data (WDFW 2020a, 2020b) show Coho Salmon (*Oncorhynchus kisutch*) as a key species present in the stream. During the WDFW fish passage evaluation in 1996, juvenile coho were observed, and one dead adult coho and redd were observed in the reach upstream

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of the crossing (WDFW 2019a). Similarly, as noted above, young of year Coho Salmon were observed both upstream and downstream of the crossing.

Statewide Washington Integrated Fish Distribution (SWIFD) and PHS data also show coastal Cutthroat Trout (*O. clarkii clarkii*) occurring both upstream and downstream of the crossing (SWIFD 2020, WDFW 2020b). Coastal cutthroat trout, which are widespread throughout small streams in Washington, prefer the uppermost portions of these streams, and can be anadromous and rear in streams for 2 to 3 years, or be resident and remain entirely in freshwater (Wydoski and Whitney 2003).

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Steelhead (*O. mykiss*) are documented in Big Creek by WDFW (2020a), and SWIFD and the PHS database indicate the presence of Rainbow Trout, the resident form of steelhead in the vicinity of the project crossing (SWIFD 2020, WDFW 2020b). Steelhead that inhabit the watershed are part of the Olympic Peninsula distinct population segment and are not currently listed under the Endangered Species Act (ESA). The WDFW online fish passage database does not list any impassable barriers between the confluence of Big Creek and the project site. Rearing and overwintering juvenile steelhead may thus disperse upstream to the project crossing.

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Table 2: Native fish species potentially present within the project area

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Species	Presence (presumed, modeled, or documented)	Data source	ESA listing
Coho salmon (*Oncorhynchus kisutch*)	Documented	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Steelhead (*Oncorhynchus mykiss*)	Presumed (documented in Big Creek)	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Coastal cutthroat (*Oncorhynchus 9ngagge 9ngagge*)	Documented	SWIFD 2020, WDFW 2020b	Not warranted

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2.6 Wildlife Connectivity

A wildlife connectivity memorandum has been prepared by WSDOT's Environmental Services Office for this site. A preliminary design to accommodate the wildlife connectivity is analyzed in this report and will be finalized in the final hydraulic design. As detailed in section 4.7, the wildlife connectivity design involves a minimum hydraulic opening that is 4 feet wider than that required for a standard stream simulation design.

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2.7 Site Assessment

A site assessment was performed of fish habitat conditions, hydraulic and geomorphic characteristics, and the culvert based on field visits, WDFW's barrier inventory report (WDFW 2020c), and a WSDOT survey. An initial visit occurred in 2020, with subsequent visits postponed until 2021 after the Covid-19 pandemic had begun to subside.

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2.7.1 *Data Collection*

Site visits were performed on five occasions to collect data and observe conditions and characteristics influencing the hydraulic design:

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- HDR visited the project site on May 18, 2020, to collect pertinent information to support development of an initial design, including bankfull width (BFW) measurements, and characterizations of instream fish habitat and floodplain conditions. Channel substrates, large wood accumulations and floodplain vegetation were characterized.
- Kleinschmidt-R2 and Kiewit visited the site on June 1, 2021 to corroborate the initial data collection findings, review the representativeness of the BFW and channel substrate measurements, and identify additional data collection needs.
- Kleinschmidt-R2 and Kiewit visited the site on June 15, 2021 to collect a bulk substrate sample, measure the hydraulic effect of natural downstream in-channel flow obstructions as it would affect hydraulic modeling predictions, and measure the typical size of mobile wood pieces upstream of the culvert as they would affect the determination of minimum freeboard requirements.
- Kleinschmidt-R2 and NHC visited the site on July 13, 2021 to support an evaluation of the long term vertical stability of the channel.
- The site was revisited on July 14 by Kleinschmidt, WSDOT, QIN, and WDFW staff to review the downstream incision and vertical stability assessment, achieve concurrence on bankfull width, and discuss regrading and streambed design options.

Field reports are presented for each visit in Appendix B. BFWs are summarized in Section 2.8.2

WSDOT also surveyed the site in March 2020. The survey extended approximately 220 feet upstream and 350 feet downstream, and covered a total roadway survey length of 350 feet. The reach surveyed comprises the project reach within which data were collected and observations made for use in developing the design. Survey information included break lines defining stream bank toes and tops and overbank areas along the channel. The data were used to generate hydraulic models and evaluate geomorphology during development of the hydraulic design.

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2.7.2 *Existing Conditions*

2.7.2.1 Culverts

Both culverts are approximately 111 feet long, 5.5 feet diameter circular corrugated metal pipes (CMPs), with their inlets encased in grout and mitered to the fill slope (Figure 6). The inlets were not observed to have significant scour around them. The stream flows and transports bedload through both culverts during high flows. The right bank culvert is at an adverse slope of -0.14 percent according to the topographic survey and traps gravel bedload. The left bank culvert slopes at 0.68 percent in the direction of flow. The crossing is aligned at a slight skew to U.S. 101 (see existing plan in Appendix E). The top of the road embankment is approximately 15 feet above the thalweg. The left culvert is accordingly generally clean of gravel and conveys low summer flows. The right culvert is offset from the main channel thalweg and its invert was noted to be bare in 2020 and covered with a significant bedload deposit during the summer of 2021. Downstream, the culverts project from the road fill slope and have equal water levels due to backwatering from the log weir downstream (Figure 7). Downstream of the outlet there was a small scour pool approximately 1.5 feet deep.

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2.7.2.2 Stream

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The reach upstream of the culverts has vegetated banks with what appears to be an alluvial, low elevation wooded floodplain, with bankfull depths between 1 feet and 2 feet. There are several pieces of large woody material (LWM) present along the stream banks throughout the upper reach, but none span the channel. The channel morphology is generally plane bed within the surveyed reach, with mostly riffle and run channel units (Figure 8). The reach substrate is composed of predominantly gravel (Figure 9), with hardpan showing through at a few locations. Starting approximately 800 feet upstream of the culverts, above the surveyed reach, the channel becomes entrenched (Figure 10), and there is more LWM present across the channel, with more pools formed in association.

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Figure 6: Culvert inlets

Figure 7: Culvert outlets

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Figure 8: Representative views of the channel upstream of US 101

Figure 9: Representative streambed material upstream of culverts

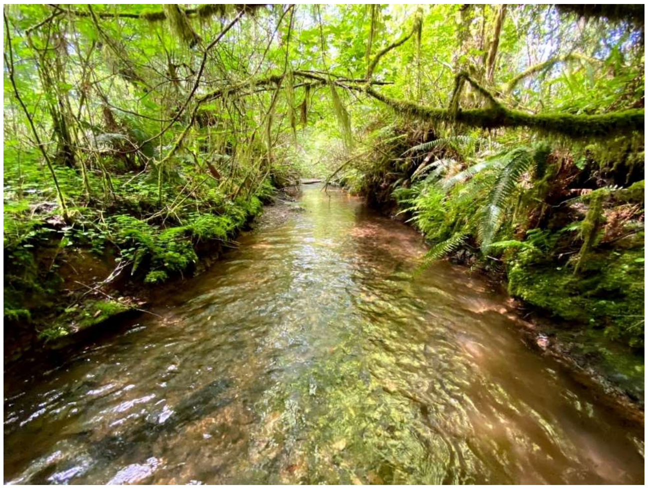

Figure 10: Start of entrenched reach upstream of surveyed reach

The log weir located approximately 30 feet downstream of the culvert outlets has an approximately 2-foot hydraulic drop (Figure 11). There are knee-deep pools 5 to 8 feet upstream of the weir. There is a second water surface drop over naturally accumulated wood a short distance below the weir. The first ELJ is located along the left bank approximately 60 feet downstream of the culvert outlets (Figure 12), and the other two are located sequentially downstream along the right bank. The channel is clearly incised downstream of the constructed weir, with streambanks around 3 to 4 feet high and the ELJs have vertical posts and toe logs that are elevated approximately 1.5 feet above the thalweg (Figures 13 and 14). The implication is that the channel has incised approximately 1.5 feet since the ELJs were constructed in 2003. Horizontal logs with rootwads are pinned to the posts with rebar. Ancient LWD embedded within exposed, weathered hardpan streambed currently presents a natural log overflow grade control near two of the ELJs.

Downstream of the ELJs, the channel widens, bank slopes are less steep, and bank heights decline as the channel approaches the indurated matrix-supported conglomerate natural grade control feature observed approximately 500 ft downstream of the crossing. The channel has more pool habitat downstream compared with upstream of the culverts, with pools formed in association with ancient buried large wood and scour at sharp bends. There is generally more LWM and gravel found downstream of the culverts than upstream, with gravel bar deposits increasing in spatial extent and volume moving in the downstream direction (Figures 15 and 16).

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2.7.2.3 Floodplain

The stream exhibits floodplain connectivity only within an approximately 500 feet long reach extending upstream of the crossing, with a bankfull depth between 1-2 feet. The channel becomes substantially entrenched moving farther upstream for at least 1,100 feet. The channel downstream of the constructed log weir has incised and remains entrenched within a relic floodplain for approximately 750 feet.

Figure 11: Log weir

Figure 12: ELJ 1

Figure 13: ELJ 2

Figure 14: ELJ 3

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Figure 15: representative LWM downstream of culverts

Figure 16: Representative view of extensive gravel deposits in downstream reach

2.7.3 *Fish Habitat Character and Quality*

Upstream, in the vicinity of the U.S. 101 crossing, the project stream flows through a predominantly deciduous mature forest consisting primarily of alder (*Alnus rubra*) and bigleaf maple (*Acer macrophyllum*), with a few western hemlock (*Tsuga heterophylla*), Douglas fir (*Pseudotsuga menziesii*), and a few large Sitka spruce (*Picea sitchensis*) at the upstream end of the reach. There is a dense shrub understory with native species including salmonberry (*Rubus spectabilis*), willows (*Salix spp.*), vine maple (*Acer circinatum*), sword fern (*Polystichum munitum*), and lady fern (*Athyrium filix-femina*). The mature forest and shrub cover provides good shading, nutrient inputs, and potential for LWM recruitment.

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Logs, rootwads, and other LWM were found to be sparse in the upstream reach. There were three places where large logs and woody material were present within the stream channel and banks, and a total of eight key pieces of LWM in the upstream reach. These logs, which ranged from 6 to 12 inches in diameter, provided some in-stream habitat complexity, cover, and bank stability. Most were located along the right and left banks including two stumps and rootwads in the right bank. The stumps were undercut, forming pools along the right bank that were 16 inches and 24 inches deep.

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WDFW estimated spawning and rearing habitat area upstream of the crossing is around 58,500 square feet (SF) and 60,000 SF, respectively, distributed over 11,266 linear feet of stream (WDFW 2020c). Instream habitat in the upstream reach comprises a series of runs and short glides, interconnected by shallow riffles. Five small pools were observed in the reach: one spanning the channel near the downstream end of the reach, and the other four located along the banks at meanders throughout the reach. The smaller pools were about 16 inches deep, and the two larger ones near the downstream end were about 24 inches deep at the time of the field visit. The undercut banks and the large stump overhanging the pool along the right bank near the downstream end of the surveyed reach provide excellent cover for fish. The pool/riffle habitat throughout the upstream reach provides good rearing habitat for the salmon species that inhabit the stream.

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Substrate in the upstream reach is predominantly gravel with small cobbles, and embedded fine sediments present in areas with lower flow velocities and near the stream margins. This substrate appears to provide spawning areas for coho, while the areas of smaller gravel provide spawning habitat for smaller species such as cutthroat trout.

Downstream of the U.S. 101 crossing, the stream flows through predominantly deciduous mature forest consisting primarily of alder and bigleaf maple, with a few western hemlock and Douglas fir. There is a dense shrub understory with native species including salmonberry, willows, vine maple, sword fern, and lady fern. The mature forest and shrub cover provides good shading, nutrient inputs, and potential for LWM recruitment.

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A large channel-wide pool is located at the culvert outlet on the upstream side of the constructed log weir. Downstream of the ELJs, there were four places where naturally occurring large logs and woody material were noted present within the stream channel and banks. A total of 12 key pieces of LWM were counted in the downstream reach, ranging from 8 to 24 inches in diameter. LWM was associated with pool formation at several locations. Instream habitat throughout the reach is composed of shallow riffles and glides with some small pools scoured along undercut banks at the outer bends of meanders. Seven of these types of pools observed in the downstream reach were between 16 and 24 inches deep. Partial cover was provided by overhanging banks, and one pool was under a large stump.

Pools, LWM, and instream habitat complexity provide good rearing habitat for coho and steelhead in the downstream reach. Gravel areas, particularly at pool tailouts, provide potential spawning areas for coho, and areas of smaller substrate in slower flows provide spawning habitat for cutthroat. Steelhead are mainstem spawners and use larger gravels in streams and tributaries that are typically larger than the UNT in the study reach. Habitat in this reach is more suited to spawning for the smaller salmon species. Steelhead juveniles disperse to rear and overwinter throughout smaller tributaries and could use the study reach throughout the year, but particularly during high flows when they retreat to smaller streams for refuge.

2.8 Geomorphology

Geomorphic information provided for this site includes selection of a reference reach, the basic geometry and cross sections of the channel, stability of the channel both vertically and laterally, and various habitat features.

2.8.1 *Reference Reach Selection*

A section of stream approximately 130 feet upstream of the culverts was identified as representative of a naturally occurring, non-incised channel, and was selected as a reference reach (Figure 17). This reach has an approximate average channel gradient of 0.9 percent. The reference reach was relied on primarily for measuring bankfull dimensions for informing the design of the hydraulic opening width and the cross-section morphology of the constructed channel outside of the replacement structure footprint. The reference reach morphology was not used to design cross-section shape and planform underneath the replacement structure because vegetation controlling bank stability cannot generally grow there.

2.8.2 *Channel Geometry*

The project stream has a gently meandering, low sinuosity planform both upstream and downstream of the crossing. Bankfull morphologies are distinct and widths are comparable in both the incised and non-incised sections. The bottom cross-section profile alternates between flat riffles and sloping point and mid-channel gravel bar deposits. The channel morphology is judged to be generally stable upstream of the crossing, consistent with Stage I of Schumm et al.'s (1984) Channel Evolution Model; downstream, the incised channel is judged to be consistent with Stage II.

Bankfull width was measured at five locations (Figure 17). BFW was determined using a tape at two locations upstream (Figure 18), and from cross-section profile surveys at three locations downstream of the crossing (Figure 19). The measurements taken downstream were in the incised channel and were not substantially different from upstream (Table 3), indicating that channel has not widened at this time in response to incision. As an independent check, the BFW estimate based on the WCDG regression equation for high-gradient, coarse-bedded streams in western Washington was calculated to be 15.1 ft, based on the basin area and mean annual precipitation (see Section 3; Barnard et al. 2013). BFW concurrence was achieved during a subsequent site visit held with the QIN and WDFW on July 14, 2021, during which time the five BFW measurement locations were revisited and measured independently by the group. A BFW design value of 15 ft was approved for the site (see field report in Appendix A).

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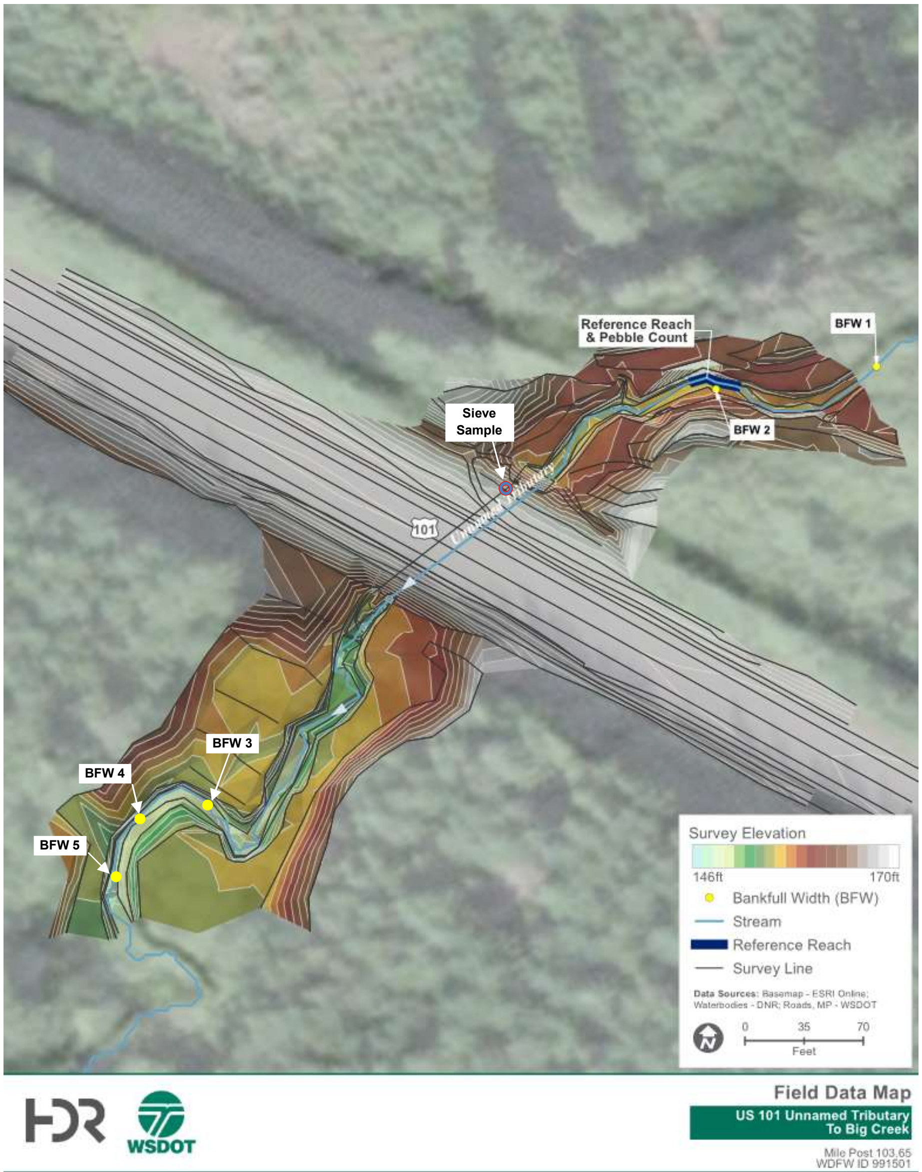

Figure 17: Reference reach and locations of BFW measurements and substrate sampling

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Table 3: Bankfull width measurements

BFW #	Width (ft)	Included in design average	Concurrence notes
1	13.0	Yes	13.9 ft Measured 7/14/21
2	14.0	Yes	15.0 ft Measured 7/14/21
3	14.7	Yes	15.9 ft Measured 7/14/21
4	13.2	Yes	14.6 ft Measured 7/14/21
5	15.8	Yes	15.4 ft Measured 7/14/21
Average	**14.1**		**Concurrence Obtained on 15.0 ft on 7/14/21**

Figure 18: Representative bankfull width measurements in non-incised reach upstream of culverts

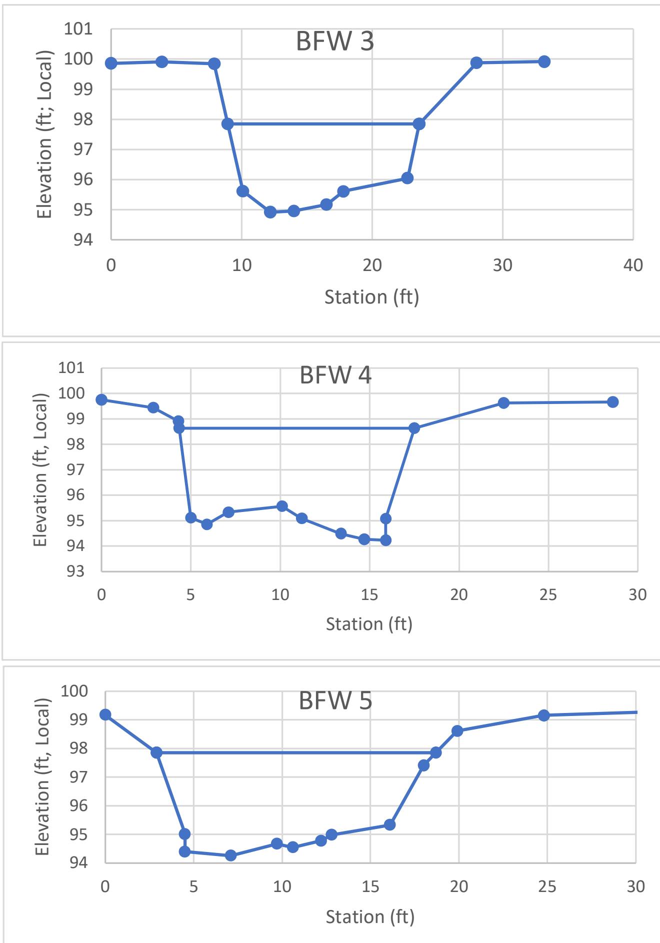

Figure 19: Cross-section profiles surveyed in 2021 for BFW determination

2.8.3 ***Sediment***

A pebble count was performed in 2020 upstream of the crossing within the reference reach, away from any visible evidence of backwater influence of the culverts. A sieve sample was subsequently collected in 2021 from bedload deposited inside the right culvert, showing the grain size distribution of material that has been recently transported by the stream. The two samples yielded similar results (Table 4). The bed material is a mixture of some coarse sand, gravel, and a few small cobbles. The largest sediment particle encountered was 4.0 inches in diameter, and was found downstream (Figure 20).

Figure 20: Largest material observed

Table 4: Sediment properties in vicinity of project crossing

Particle size	Pebble Count Diameter (in)	Pebble Count Diameter (mm)	Sieve Sample Diameter (in)	Sieve Sample Diameter (mm)
$\mathbf{D_{16}}$	0.3	8	0.5	12
$\mathbf{D_{50}}$	0.7	18	0.7	17
$\mathbf{D_{84}}$	1.4	36	1.5	37
$\mathbf{D_{95}}$	2.1	53	2.1	55
$\mathbf{D_{max}}$	4.0	102	-	-

2.8.4 *Vertical Channel Stability*

The project stream exhibits evidence of significant incision downstream of the culverts over the past 20 years that will affect the design of foundation depth of the replacement structure. As described in Section 2.2, the project site is located on the distal end of an ancient alluvial fan built out onto a weathered Pleistocene glacial outwash deposit. The two deposits are associated with spatially discontinuous layers of soil horizons with contrasting erosional properties. Currently, the channel and relic floodplain are inset 5-12 feet below the surrounding topography (Figure 21). The relic floodplain is between 80-150 feet wide with large tree stumps present, indicating that surface formed long before historic timber harvest activity. The channel appears to be hydrologically connected to its surrounding floodplain at more frequent flood flows at two locations: within the first 500 feet upstream of the crossing, and a reach downstream of the surveyed reach. Farther upstream, the channel becomes hydrologically disconnected from the floodplain over at least a 1,100 feet distance (Figure 21). Overall, different portions of the channel and floodplain are in various stages of channel evolution, from Stages II to V (Schumm et al. 1984), reflecting a channel morphology that is in spatially variable flux. Such conditions can affect long term stability of the streambed profile.

Downstream of the constructed weir, the three associated ELJs do not appear to have prevented or precluded subsequent scouring of the erodible silt parent material underlying the surface gravel deposits. Nonetheless, despite the incision, stream banks have remained steep and the bankfull channel has not widened substantially in most locations because of the cohesive properties of the silt and conglomerate at bank toes. Correspondingly, the channel bed downstream of the weir degraded further, rather than channel widening and progressive stages of channel evolution as one might except in alluvial bank and bed soils.

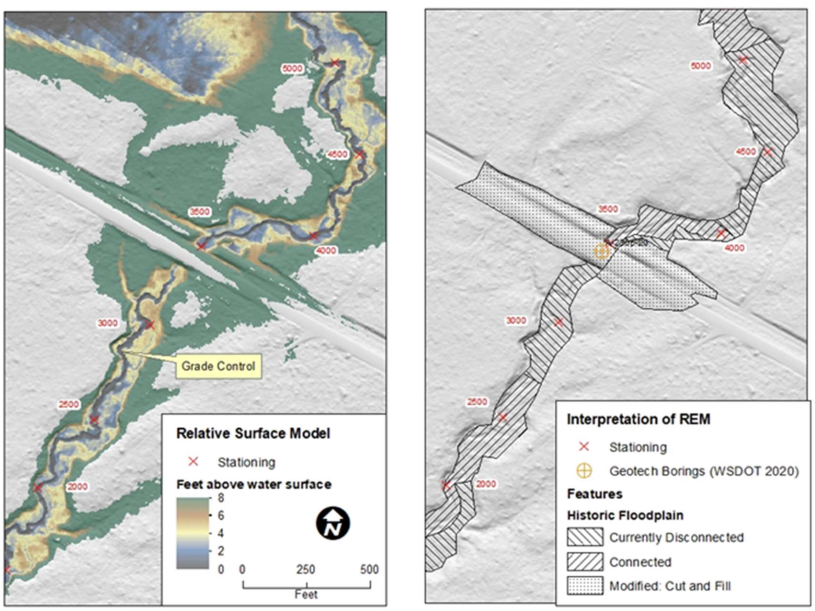

Figure 21: LiDAR based Relative Surface Model, showing surfaces relative to the water surface with profile stationing. Floodplains that are 3 feet or less above the water surface are most likely to be hydrologically connected at more frequent flood levels

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The vertical stability of the channel was inferred from the longitudinal channel profile, topographic models, comparing as-builts of the ELJs with present streambed elevations, and field observations. Recent LiDAR bare-earth surface model data (USGS and Quantum Spatial 2019) was used to develop a longitudinal channel profile extending 3500 feet both upstream and downstream of the culverts (Figure 22). General comparisons of the LiDAR data with WSDOT survey data at this and other sites indicates that the LiDAR-based profile away from the road prism is higher than the surveyed channel bed elevations, but the bias appears to be consistent (Figure 22).

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The profile indicates specific breaks in the channel gradient along the tributary that influence spatial variation in sediment transport and deposition patterns. Three primary breaks in the profile are apparent, moving from downstream to upstream: (i) a convex gradient break at the approximate location of an apparent geological grade control; (ii) the knickpoint at the constructed log weir downstream of US 101; and (iii) a concave gradient break is located approximately 500-700 feet upstream. The two slope breaks are associated with incised channels downstream and upstream of each break location, respectively. The overall gradient is reduced in the vicinity of the road crossing compared with upstream and downstream (Figure 22). The average gradient well upstream of the culverts is 1.3 percent. Beginning 1250 feet downstream to Big Creek the average gradient remains steady at around 1.0 percent, along a grade approximately parallel to the 0.97 percent grade in the non-incised reach upstream of the culvert. Wood-forced steps embedded in the streambed appear to help maintain the relatively steep gradient within these two reaches. The grade within the incised reach below the log weir and ELJs is lower, around 0.63 percent, and it is evident from the profile that there has been local degradation within that reach extending down to the geological grade control.

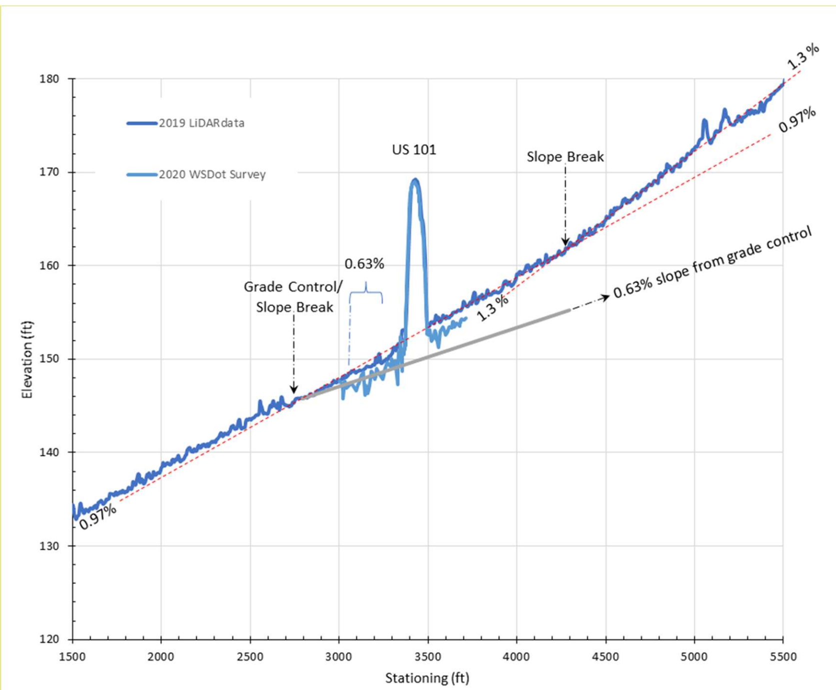

Figure 22: Large scale LiDAR and surveyed longitudinal elevation profiles encompassing project reach; red dashed lines depict grades of incised and non-incised reaches upstream of culverts; plausible maximum extent of future incision indicated by gray line

2.8.4.1 Potential for Aggradation.

Historical timber harvest practices likely increased rates of sediment delivery, wood loading, and peak flows in the stream compared with present day and what can be expected in the future with more protective BMPs and buffer zone requirements. With more conservative timber harvest practices and associated protective buffer width requirements in effect since 2005, sediment yields are expected to decline with time and return to a more natural level. The timing and degree of change in sediment yields have not been measured at the project site. However, a photograph taken in 2004 provides perspective on the scale of the more recent changes the channel downstream has experienced over the past 17 years. The constructed log weir, which presently has an approximately 1.5-2 feet drop below it (Figure 11), appears to have been buried previously by gravel upstream and downstream over a substantial portion of its length (Figure 22). It is unclear if gravel recruitment to the stream prior to 2004 was a legacy of timber harvest impacts and incision, but this mechanism is plausible. There is a low potential of landslides or debris flow type sediment delivery in the watershed (Section 2.2) and historical clearcut logging within the riparian zone likely created spikes in sediment delivery and greater peak runoff rates that could have accelerated incision.

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In the absence of these episodic sources, gravel recruitment in the future will likely be constrained to be primarily from further erosion of the channel boundary. With regrading of the channel and corresponding lowering of the base level control below the culverts, upstream channel incision and channel evolution will likely entrain more sediment. An aggradation-degradation episode on the order of two to three feet may be inferred to have occurred based on design plans for the weir and ELJs provided by WDFW, a photo of the weir taken in 2004 (Figure 23), and the current bed configuration. Future variability in the basins hydrology and bed material supply may generate similar variability in the bed elevation in the future, albeit to a lesser extent than historically because of more protective timber harvest practices in force. The scale of the channel limits movement of large wood and propensity to form large jams, so aggradation based on large wood would be limited only to accumulation of material above blockages formed by recruitment of timber adjacent to the channel. The expected maximum aggradation heights would scale with the diameter of wood available for recruitment (1-2 feet diameter). Because the channel is expected to regrade and potentially downcut further within the vicinity of the culverts, increasing the freeboard of the proposed crossing to also account for localized aggradation above installed LWM does not appear to be required at this crossing, and future aggradation at the crossing is generally unlikely overall.

2.8.4.2 Potential for Degradation

The channel shows signs of recent channel degradation into weathered cohesive silt. Upstream, the channel laterally erodes both a sandy hardpan and overlying alluvium. Downstream of the culvert we observed limited migration of individual meander bends within the relic floodplain soils, where recent channel incision has exhumed old, buried large wood pieces and indurated conglomerate. Where present, these features act as bank armoring and grade-controls, but they are spatially discontinuous. Soils around and under the stream are interpreted to consist of a patchwork of readily eroded noncohesive gravel and cohesive silt. Discontinuous, layered bank soil, buried wood pieces and erodible subsurface material near the project site means there is the potential for significant long term channel degradation once the existing culverts are removed and they become exposed.

Figure 23: Photograph taken in 2004 showing extensive gravel deposit below culverts and constructed log grade control (copied from WDFW 2019a)

The existing exhumed wood and exposed hardpan grade controls dispersed sporadically downstream of US 101 are susceptible to degradation over the long term owing to their soft character. Natural buried wood steps downstream of the confluence could deteriorate and possibly wash out, allowing the channel to incise further. A more resistant grade control was found farther downstream, in the form of an outcropping of indurated, matrix-supported gravelly conglomerate. The conglomerate presents as a subtle slope break in the channel profile at approximately Station 2270 in the long profile depicted in Figure 22. We found no applicable reference for rates of channel incision in such material. However, it is plausible that the conglomerate could deteriorate, lowering the grade control up to about one foot over the engineering design-life of the proposed culvert, which would lower the elevation of the feature to approximately 145 feet (NAVD88 datum). This indurated conglomerate appears to set the base level grade control for upstream presently, such that lowering of the channel at this point could conceivably propagate upstream and further regrade the channel. The local gradient upstream of a current grade control between the conglomerate and the constructed log weir has an approximate average gradient of about 0.63 percent. This value may be a reasonable empirical estimate of the potential regrade slope that could extend upstream of the conglomerate over the next 50+ years with existing channel roughness in place. With additional roughness, the potential slope could be steeper. Combining the one foot of lowering at the grade control feature with the distance upstream to the crossing sets the minimum plausible channel grade at the downstream side of the crossing to be about 171.5 feet. Because this elevation is based on several conservative additive assumptions, we believe it is relatively unlikely that the creek bed will reach this elevation over the design life of the culvert. Nonetheless, given the range of bed elevation changes that have been observed to occur within the project reach over a

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relatively short time frame, it appears prudent to design the foundation depth of a replacement structure accordingly.

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Similar types of grade controls were not observed within the hydrologically connected reach upstream of the culverts. It is likely that the downstream incision would propagate upstream following removal of the grade control presently provided by the log weir and existing culverts, potentially disconnecting the floodplain and any off-channel habitats upstream of the crossing site, between the two existing incised channel sections.

2.8.5 *Channel Migration*

Channel migration was assessed based on topography and field observations. The stream is too small and canopy too thick for aerial photography to be of use for evaluating migration history. The channel within the survey extents has fairly low sinuosity, and stream banks are vertical at many locations and are composed of a hardpan-gravel conglomerate, Although there is evidence in Figure 21 of historic channel migration upstream, the meander planform footprints appear relatively stable on a structural design time scale. The low sinuosity of the channel and the cut in the old adjacent grade that runs parallel to the road is expected to constrain future migration at the upstream approach, and the floodplain immediately downstream of the crossing is seen to be entrenched and relatively narrow, which also should present as a constraint. In addition, despite the strong evidence of incision, the vegetated, vertical banks, and similarity between the BFW downstream and upstream in both incised and non-incised reaches, respectively, are indicative of a general lateral stability. Channel widening and meander migration in the vicinity of the replacement culvert inlet and outlet are accordingly expected to be limited as the stream channel regrades vertically. Overall, the weight of the evidence indicates the risk of significant channel migration in the vicinity of the crossing appears to be low.

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2.8.6 *Riparian Conditions, Large Wood, and Other Habitat Features*

The streambanks upstream of the US 101 crossing are vegetated and abut wooded floodplains that contain regrowth from previous clearcuts. The riparian corridor is comprised predominantly of deciduous mature forest cover of large alders, with a few conifers. Beyond the areas adjacent to the stream channel, the forest becomes evergreen, predominantly Douglas fir. A recent clearcut on the North side uplands left a wide riparian management zone (RMZ) consistent with current timber harvest requirements. There is a moderately dense shrub understory with native species including salmonberry, willows, vine maple, and ferns. The forest canopy within the existing RMZ overall provides good shade, nutrient inputs, and potential LWM recruitment. Logs, rootwads, and other LWM, however, were not abundant within the channel in the upstream reach. There were three places where large logs and woody material were present within the stream channel and banks creating some instream cover and sediment retention. Most were located along the right and left banks including two stumps and rootwads in the right bank that were undercut, forming small pools. Just upstream of the culverts, a small tributary comes in on the right bank, creating a deep scour hole on the left undercut bank.

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Downstream of the US 101 crossing, the stream flows through predominantly deciduous mature forest consisting of alder and bigleaf maple, with a few western hemlock and Douglas fir. Alders are the predominant species along the channel banks, with conifer species including Douglas fir the dominant tree cover beyond. The forest was logged recently, but in accordance with Washington State's HCP timber harvest practices, a wide riparian management zone was left intact. A dense shrub understory on both banks consists largely of native species including salmonberry, vine maple, and willows. The mature forest and shrub understory provides good shading over the stream channel, as well as nutrient inputs, cover, and potential LWM recruitment. The channel in the downstream reach has vegetated banks throughout and is less confined than upstream, with a wooded floodplain.

There is relatively little large wood in the channel upstream of the culverts within the first 500 feet. There is ancient wood creating habitat complexity in the channel farther upstream, including some very old, glacial era exposed logs embedded in hardpan on the stream bottom. There are several locations downstream of the culverts, including in the vicinity of the ELJs, where grade control is provided by similarly old, embedded logs. A more recently formed, natural log accumulation has created an approximately 1-1.5 ft hydraulic drop and formed a pool a short distance downstream of the constructed log weir. Downstream of the ELJs there were four places noted in the surveyed reach where naturally occurring large logs and woody material were present within the stream channel and banks. LWM was contributing to pool formation at several locations. Undercut banks and small scour pools were present around the ELJs, and along the outside of meander bends. One pool was observed near the downstream end of the surveyed reach in association with a 3-foot-diameter stump.

WDFW completed a physical habitat survey in 1996 at the site, which reported a high number of wind-fallen trees across the stream, and clear-cut areas off the left bank approximately 1,800 feet upstream, and off the right bank approximately 3,000 feet upstream of the crossing (WDFW 2019b). No beaver dams or activity were reported, and none were observed in 2020 and 2021 field visits.

3 Hydrology and Peak Flow Estimates

The project stream drains an 29ngagged basin, with no long-term historical flow data available. No hydrologic studies, models, or reports were found that summarized peak flows in the basin. Consequently, USGS regression equations (Mastin et al. 2016; Region 4) were used to estimate peak flows at the U.S. 101 crossing. Inputs to the regression equation included basin size and mean annual precipitation. UNT to Big Creek has a basin area of 0.77 square mile and a mean annual precipitation within the basin of 113.0 inches (PRISM Climate Group 2019). The basin was delineated from LiDAR data acquired from the Washington DNR LiDAR Portal (USGS and Quantum Spatial 2019) using Arc Hydro.

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The resulting regression estimates (Table 5) were evaluated for potential sub-regional bias by comparing regression predictions against estimates derived at selected stream gages in the area using available flow records. A Washington Department of Ecology gage was identified from the Wishkah River, but only USGS gages were found with a sufficiently long period of record (>20 years) in the area to permit evaluating the larger predicted flood peaks (Table 6).

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Peak flow data were analyzed for each gage following the Bulletin 17B methodology for peak flow frequency analysis, using the Hydraulic Engineering Center's Statistical Software Package (HEC-SSP) version 2.2. HEC-SSP uses the Log Pearson Type III distribution for annual peak flows on unregulated streams, fit by the Method of Moments. Distribution parameters were estimated for the 2-, 10-, 100-, and 500-year return intervals based on moments of the sample data (site-specific). Adjustments were made for non-standard data, low outliers, and historical events. The resulting peak flow estimates were compared against the regression estimates using the equations in Mastin et al. (2016), where drainage area and mean annual precipitation estimates were determined using USGS' StreamStats web application. The ratio of gage-based to regression-based estimates was then plotted against drainage area (Figure 24). The results indicate that the regression estimates for smaller basins may be generally comparable to or higher than would be derived using gage data. As corroboration, a modeling exercise performed for Culvert ID 993704 using the MGS Flood model indicated that the regression estimates for a similarly sized, nearby drainage area were higher than values estimated based on a more direct simulation of stormwater rainfall-runoff processes. The regression estimates accordingly appear to be more conservative.

Table 5: USGS regression-based estimates of peak flow

Mean recurrence interval (MRI)	USGS regression equation (Region 4) (cfs)	Regression standard error (percent)
2	80.8	52.5
10	135	50.5
25	161	51.7
50	181	52.9
100	203	54.2
500	249	58.0
2080 predicted 100	243	NA

Table 6: Local USGS Gages Used to Evaluate Bias in USGS Regression Predictions

Station #	Gage Name	Years of Record
12039005	Humptulips River Below Hwy 101	2002-2018
12036000	Wynoochee River Above Save Creek Near Aberdeen, WA	1952-2018
12035500	Wynoochee River At Oxbow Near Aberdeen, WA	1925-1952
12035450	Big Creek near Grisdale, WA	1972-1996
12035400	Wynoochee River near Grisdale, WA	1965-2018
12039050	Big Creek near Hoquiam, WA	1949-1970
12039100	Big Creek Tributary near Hoquiam, WA	1949-1968

Consequently, the regression estimates in Table 4 were used in design development, to provide a safety factor when designing for flood conveyance, freeboard, channel stability, and scour. For more information on the 2080 predicted 100-year flow determination see Section 7.2.

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Summer low-flow conditions are unknown and high/low fish passage design flows are not included in this analysis. The stream was observed to be flowing in mid-August 2021.

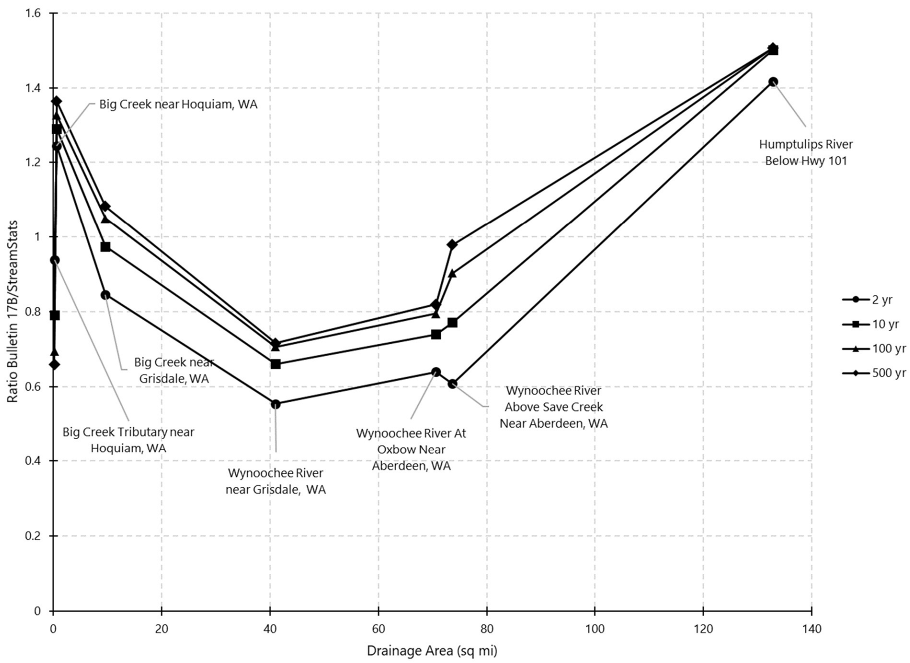

Figure 24: Ratio of gage-based flood peak magnitudes vs. regression-based estimates, plotted against drainage area

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4 Hydraulic Analysis and Design

The hydraulic analysis of the existing and proposed U.S. 101 UNT to Big Creek crossing was performed using the United States Bureau of Reclamation's (USBR's) SRH-2D Version 3.3.0 computer program, a two-dimensional (2D) hydraulic and sediment transport numerical model (USBR 2017). Pre- and post-processing for this model was completed using SMS Version 13.1.13 (Aquaveo 2021).

Three scenarios were analyzed for determining stream characteristics for UNT to Big Creek with the SRH-2D models: (1) existing conditions with twin barrel 66-inch-diameter CMP culverts, (2) natural conditions with the roadway embankment removed within the flooding extents and the channel graded, and (3) future conditions with the proposed 20-foot hydraulic opening.

4.1 Model Development

This section describes the development of the model used for the hydraulic analysis and design.

4.1.1 *Topographic and Bathymetric Data*

The channel geometry data in the model were obtained from the MicroStation and InRoads files supplied by the Project Engineer's Office (PEO), which were developed from topographic surveys performed by WSDOT in March 2020. The survey data were supplemented with QL1 LiDAR data with a 3-foot cell size from the Washington DNR LiDAR Portal (USGS and Quantum Spatial 2019) to extend the floodplain extents. The proposed grading surface was created by HDR. All survey and LiDAR information is referenced against the North American Vertical Datum of 1988 (NAVD88).

4.1.2 *Model Extents and Computational Mesh*

The hydraulic model extents correspond to the detailed survey data extents, approximately 220 feet upstream of the existing culvert inlet and 350 feet downstream of the culvert outlet measured along the channel centerline. A boundary condition sensitivity analysis was conducted to confirm that the model boundaries are sufficiently far away from the areas of interest not to influence the hydraulic results. LiDAR data were used to extend the model domain laterally to capture the flooding extents.

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The computational mesh consists of both patched (quadrilateral) and paved (triangular) elements, with finer resolution in the channel and larger elements in the floodplain. The existing conditions domain covers a total area of 156,145 SF, with 8,433 quadrilateral and 14,695 triangular elements (Figure 25). The natural and proposed conditions domains cover a total area of 155,188 SF, with 8,824 quadrilateral and 13,495 triangular mesh elements (Figures 26, 27).

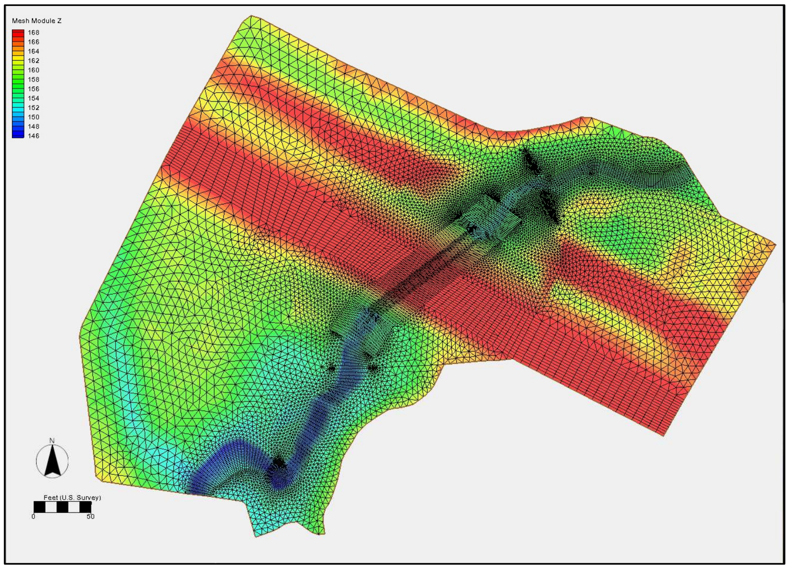

Figure 25: Existing conditions computational mesh with underlying terrain

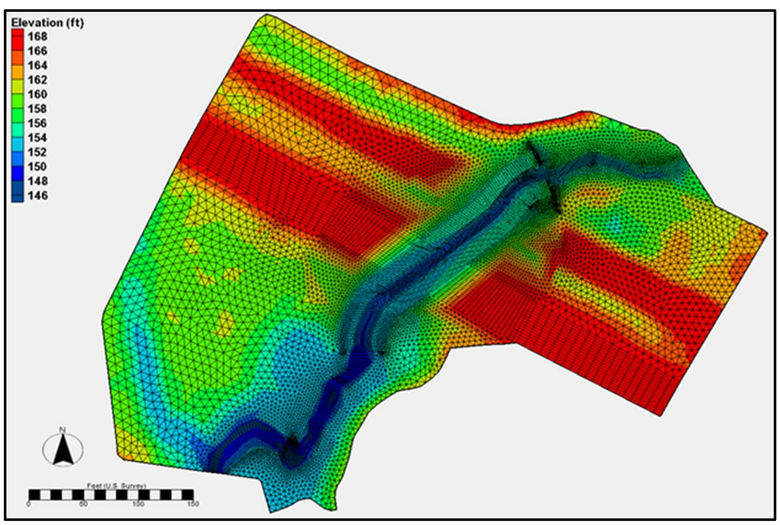

Figure 26: Natural conditions computational mesh with underlying terrain

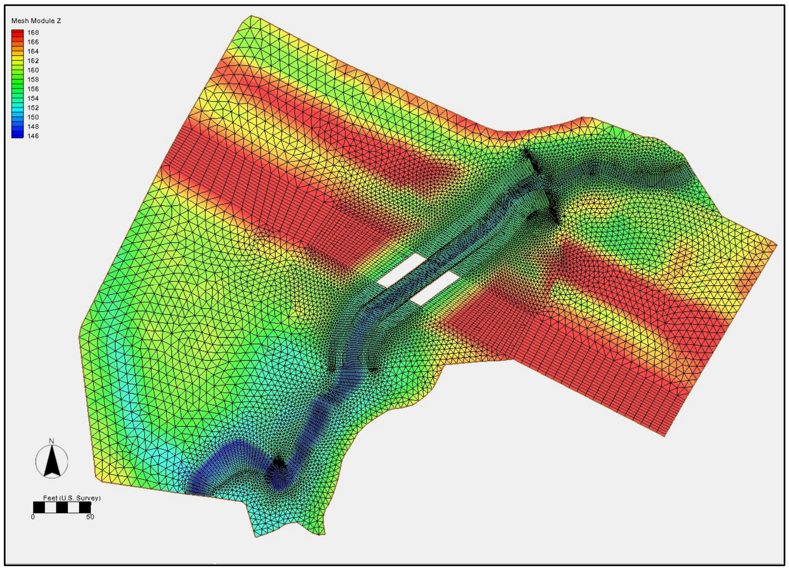

Figure 27: Proposed conditions computational mesh with underlying terrain

4.1.3 *Materials/Roughness*

Manning's n values were estimated for the natural channel and floodplain of the project stream using the Cowan method based on site observations (Arcement and Schneider (1989); see Appendix G). The resulting values were consistent with standard engineering values for 1-D simulations (Barnes 1967). Because bank stabilizing vegetation is not expected to grow inside the structure, the channel there will have a dominant bed material composed of gravel and small cobble. The value for the culvert was estimated using the same reference, with a base value of n=0.035 for a gravel-cobble mix, and with 0.01 added to account for low profile bedforms that will be part of the final design (see Section 4.4). The resulting 1-D values were then adjusted down by 10 percent to reflect generally expected reductions when moving to a 2-D model parameterization (Robinson et al. 2019; Table 6). Figures 28, 29 and 30 depict the modeled spatial distributions of hydraulic roughness coefficient values for existing, natural, and proposed conditions, respectively.

Table 7: Manning's n hydraulic roughness coefficient values used in the SRH-2D model

Land cover type	Manning's n
Channel	0.067
Overbank	0.103
Road Prism	0.02
Proposed Structure	0.041

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Figure 28: Spatial distribution of roughness values in SRH-2D existing-conditions model

Figure 29: Spatial distribution of roughness values in SRH-2D natural-conditions model

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Figure 30: Spatial distribution of roughness values in SRH-2D proposed-conditions model

4.1.4 *Boundary Conditions*

Model simulations were performed using discharges ranging from the 2-year to 500-year peak flow events summarized in Section 3. External boundary conditions were applied at the upstream and downstream boundaries of the model domain and remained the same between the existing- and proposed-conditions runs. A time series of flow rate was specified at the upstream boundary. Figure 31 depicts the simulated flow rates at the upstream boundary. The time series flow rate option was used at the upstream boundary to improve model stability. The flow was increased gradually from zero to peak flow with a time increment of 0.1 hour (6 minutes). A normal depth rating curve was specified at the downstream boundary (Figure 32). The rating curve was developed within SMS using the existing terrain, a downstream slope of 1.7 percent as measured from the terrain data, and a composite roughness of 0.0789 (calculated as 0.67*0.067+0.33*0.103, where 0.067 = Manning's n for the channel and 0.103 = Manning's n for the overbank area).

An HY-8 internal boundary condition was specified in the existing-conditions model to represent the existing circular CMP culvert crossing. The existing crossing was modeled as twin 5.5-foot-diameter circular pipes within HY-8 (Figures 33, 34). A Manning's roughness of 0.024 was assigned to the culverts. The culverts were assumed to have an embedment depth of 0 feet and free from any stream material within the barrels. Figures 35, 36 and 37 depict locations of boundary conditions in the existing, natural, and proposed conditions models, respectively.

A symmetry (slip) boundary condition was specified in the proposed-conditions model to better represent flow inside the proposed structure. Under default conditions, SMS assumes a no-slip (0 foot

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per second [ft/s]) condition at the edges of the mesh. The boundary layer of 0 ft/s would be very thin against the smooth structure surface. The mesh is too coarse to accurately capture the boundary layer; therefore, it is more appropriate to use a slip boundary condition, which does not force velocities to 0 ft/s at the mesh boundary. See Figure 36 for a map showing the location of each boundary condition in the proposed-conditions model.

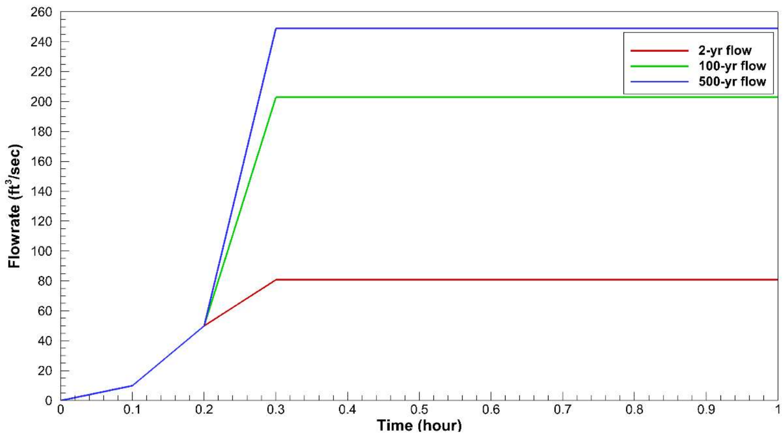

Figure 31: Simulated flow rates at the Upstream Boundary

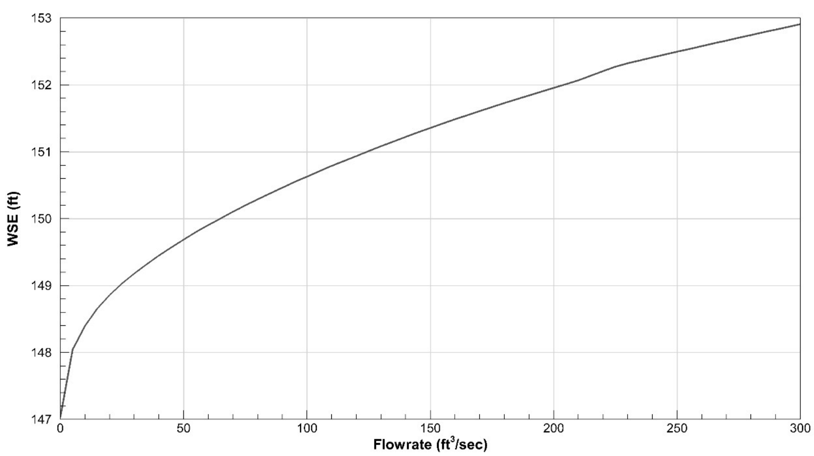

Figure 32: Downstream normal depth rating curve

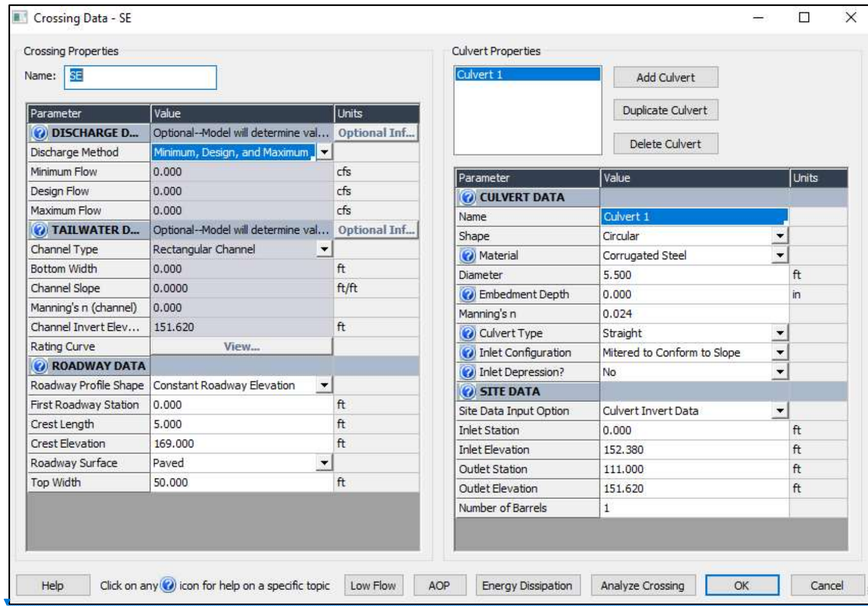

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Figure 33: Left side culvert HY-8 parameters

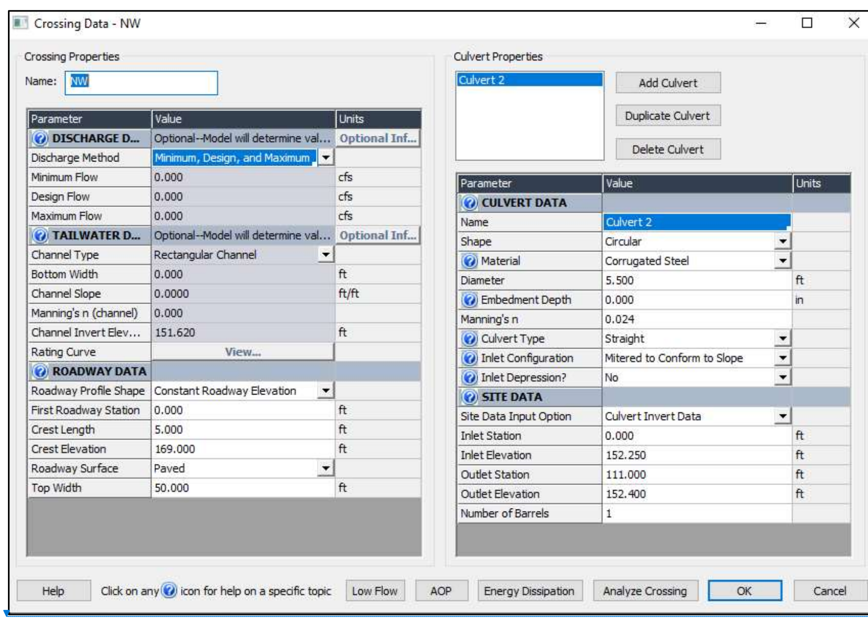

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Figure 34: Right side culvert HY-8 parameters

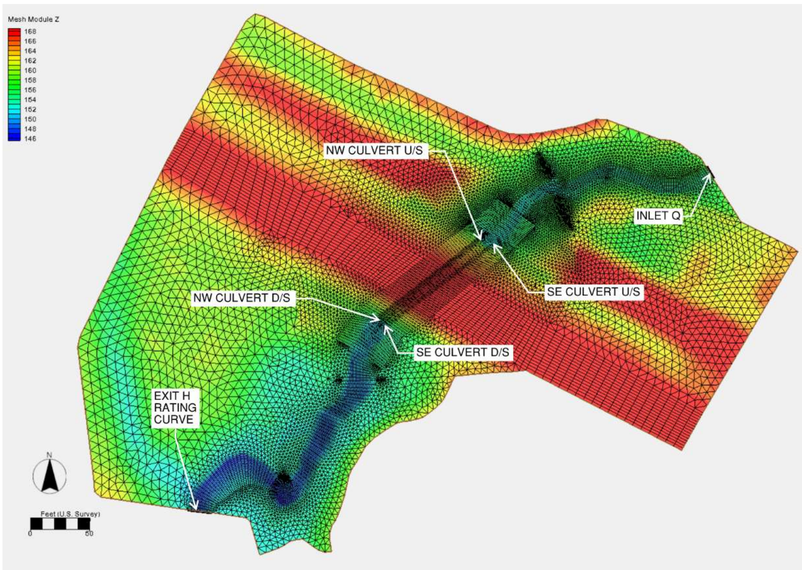

Figure 35: Location of boundary conditions for the existing conditions model

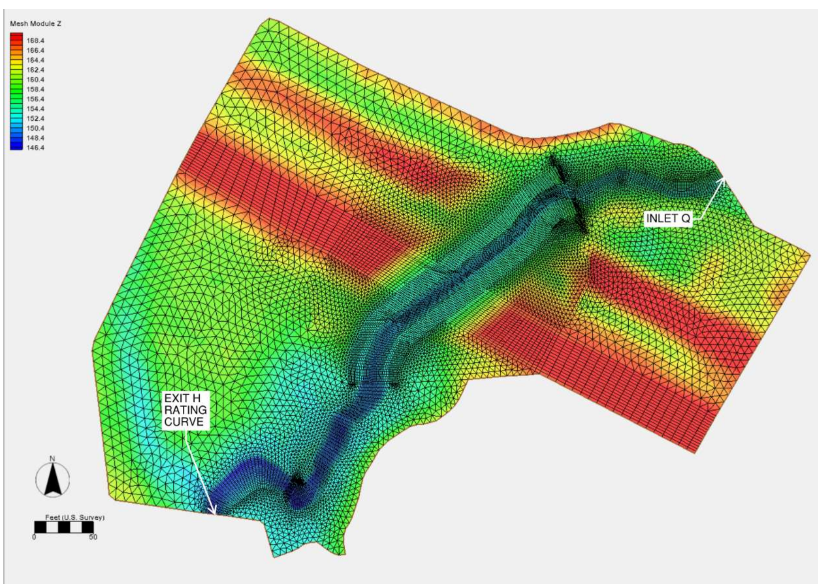

Figure 36: Locations of boundary conditions for natural conditions model

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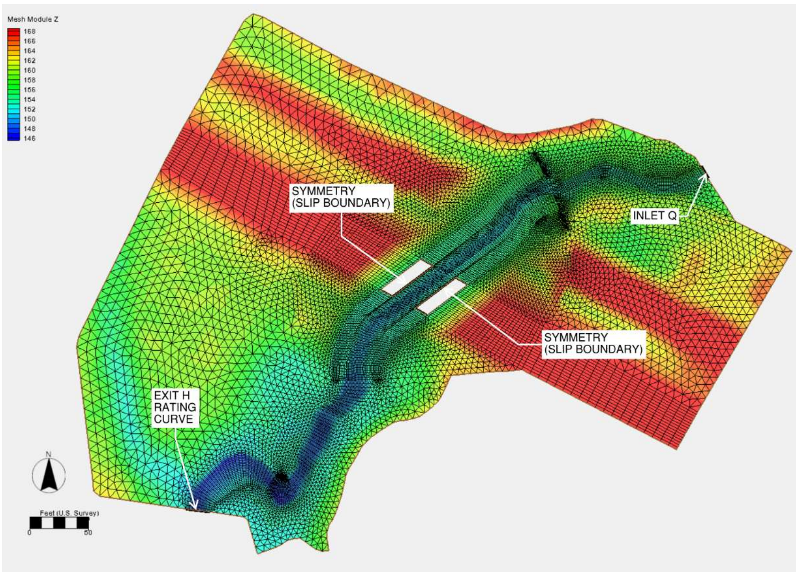

Figure 37: Locations of boundary conditions for proposed conditions model

4.1.5 ***Model Run Controls***

The model controls used in the simulation for every flow event are depicted in Figure 38. The result output frequency used was once per 5 minutes (0.083 hour) to begin with in order to troubleshoot the model and gradually to every 15 minutes (0.25 hour) once the model was stable.

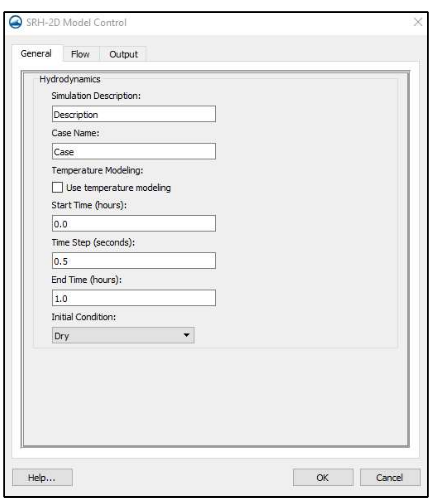

Figure 38: Model controls

4.1.6 *Model Assumptions and Limitations*

The SRH-2D hydraulic model was developed to determine the minimum hydraulic structure opening, establish the proposed structure low chord elevation (and associated freeboard), and characterize hydraulic parameters used to design the crossing. There are several attributes of the data relied upon to develop the model that affect the resolution to which model output should be relied on. In particular, the survey data collected for developing the model terrain geometry were sufficient to capture macroscale variation in channel form and floodplain topography on the order of average channel width/depth/location and floodplain gradients. The spatial scatter of the survey point data was too coarse, however, to develop a model terrain capable of discerning an accurate and precise resolution of velocity distributions at smaller microtopographic scales, precluding predicting rapid spatial variation in hydraulic properties in association with bedform and instream roughness and flow obstruction variation. Accordingly, the designs are based on general, spatially averaged model predictions of velocity and shear stress, with an appropriate safety factor. Small scale variations in hydraulic properties should not be interpreted as signifying a meaningful feature of the design. Highly detailed design modeling of large wood structures is therefore not warranted, where structure stability and scour can be designed sufficiently using simply water depth and average channel values of velocity predicted by the model and increasing roughness locally.

The use of a steady peak inflow rate is an appropriate assumption to meet design objectives at this site. Using a steady peak inflow rate provides a conservative estimate of inundation extents and water surface elevation (WSEL) associated with a given peak flow, which is used to determine the structure size and low chord. Similarly, the model predictions of peak velocity are used to design general channel morphology, streambed composition, and both loose and fixed LWM stability. Each scenario is run for a sufficient time to fill storage areas and for water surface elevations to stabilize until flow upstream equals flow downstream. This modeling method does not account for the attenuation of peak flows between the actual upstream and downstream hydrographs, in particular with a large amount of storage upstream of the existing undersized culvert. During an actual runoff event, it is unlikely that the area upstream of the culvert would fill up entirely. An unsteady simulation could be used to route a hydrograph through the model to estimate peak flow attenuation for existing and proposed conditions. During an unsteady simulation, the areas upstream of the existing culvert would act as storage and, as a result, the flow downstream of the crossing would likely be less than the current design peak flow event. This is expected to be less of an issue for the natural conditions and proposed PHD scenarios at this site, however, where the channel size is small relative to the hydraulic opening, and the channel slope too steep, for flow attenuation effects to be significant.

The SRH-2D model outputs an estimate of shear stress that is calculated using a 2-D vector adaptation of the 1-D uniform flow approximation based on depth and energy slope. The program substitutes Manning's equation to calculate the slope, which results in shear stress estimate being proportional to the square of the Manning's n coefficient. Because Manning's n is used in the modeling as a surrogate for various energy losses n addition to grain friction, the resulting estimates of shear stress cannot be used to size streambed substrates or evaluate local scour depth. Values are presented in this report for general reference, but should be treated generally as substantial over-estimates of the actual boundary shear stress (e.g., Pasternack et al. 2006). This is addressed directly in Section 5.1.

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The model results and recommendations in this report are based on the conditions of the project site and the associated watershed at the time of this study. Any modifications to the site, man-made or natural, could alter the analysis, findings, and recommendations contained herein and could invalidate the analysis, findings, and recommendations. Site conditions, completion of upstream or downstream projects, upstream or downstream land use changes, climate changes, vegetation changes, maintenance practice changes, or other factors may change over time. Additional analysis or updates may be required in the future as a result of these changes.

4.2 Existing Conditions Model Results

Locations of the cross sections used for presenting the results for existing-, natural-, and proposed-conditions models are shown in Figure 39, with longitudinal profile stationing depicted in Figure 40. Three cross sections are located upstream and three downstream, with one in the center of the structure that is used only to report natural- and proposed-conditions results. Hydraulic results for the existing conditions simulations are summarized across the main channel for the upstream and downstream cross sections in Table 8. Velocities are listed for main channel and left and right overbank (LOB, ROB) areas in Table 9. Under existing conditions, the culverts have capacity to convey all modeled flows without overtopping U.S. 101. Backwatering at the 100- and 500-year events extends upstream (Figure 41). Typical upstream and downstream cross sections are presented in Figures 42 and 43, respectively. The downstream cross section shows the 2-year flood to be substantially below the entrenched floodplain, whereas the upstream cross section is indicative a more hydrologically connected floodplain, consistent with the observations discussed in Section 2.8.4. The results of all cross sections are presented in Appendix C. Figure 44 shows the velocity contours for existing conditions model with 100-year flow conditions. Upstream velocities were lower than downstream because of backwater and differences in channel entrenchment. Fastest velocities were predicted over the constructed log weir.

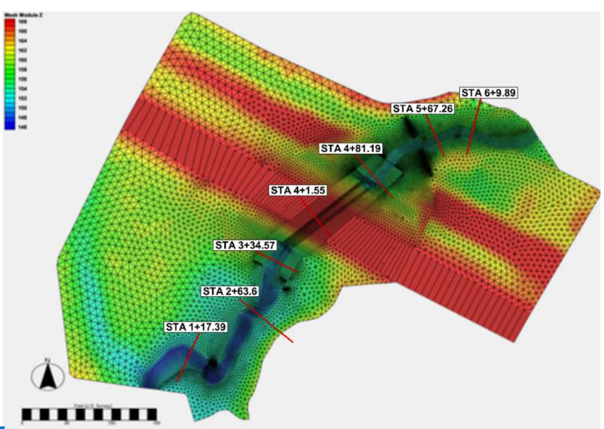

Figure 39: Locations of cross sections used for results reporting

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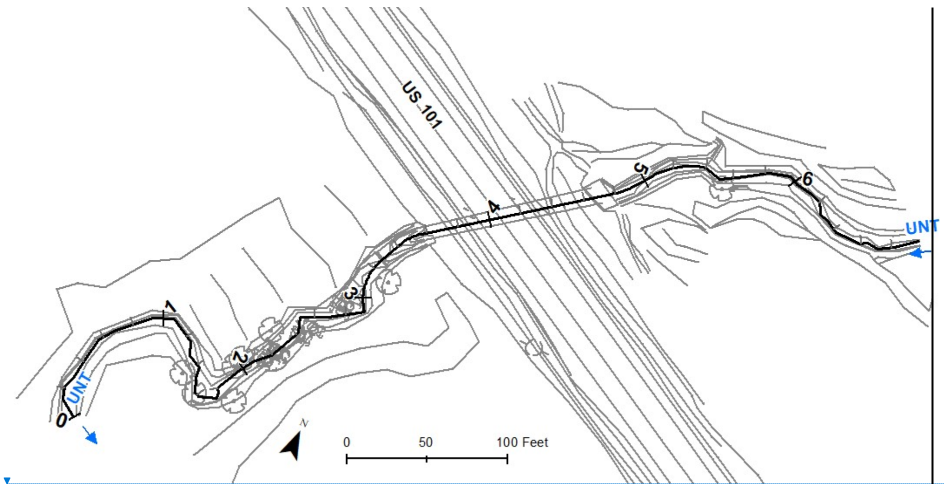

Figure 40: Longitudinal profile stationing for existing, natural, and proposed conditions

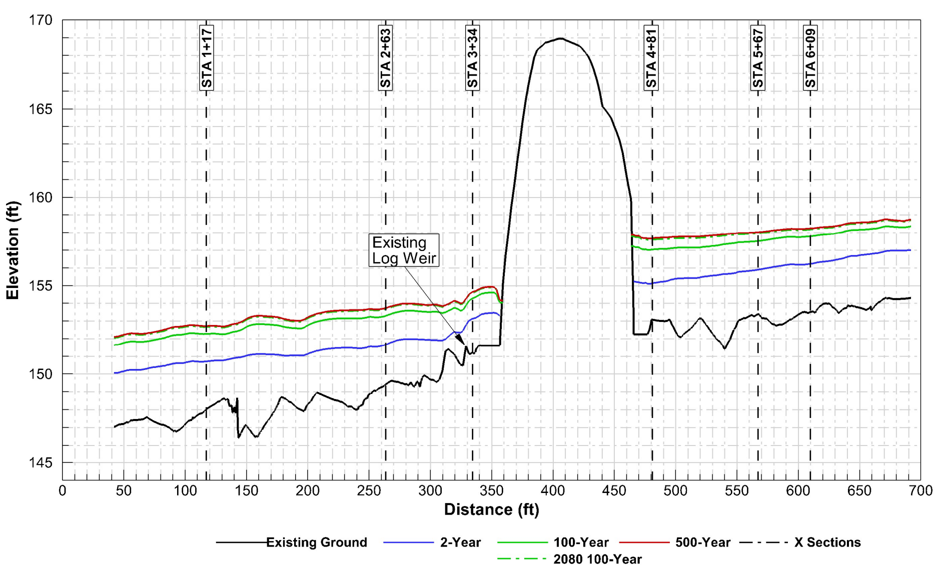

Figure 41: Existing-conditions water surface profiles

Table 8: Hydraulic results for existing conditions within the main channel

Hydraulic parameter	Cross section (STA)	2-year	100-year	2080 100-year	500-year
Average water surface elevation (ft)	1+17.39	150.7	152.2	152.6	152.6
	2+63.60	151.7	153.3	153.7	153.7
	3+34.57	153.1	154.2	154.6	154.6
	4+81.19	155.1	157.0	157.6	157.7
	5+67.26	155.9	157.5	158.0	158.0
	6+09.89	156.2	157.8	158.2	158.2
Max water depth (ft)	1+17.39	2.7	4.3	4.7	4.7
	2+63.60	2.3	3.9	4.3	4.4
	3+34.57	3.3	4.5	4.8	4.8
	4+81.19	2.5	4.4	4.9	5.0
	5+67.26	2.8	4.4	4.8	4.9
	6+09.89	2.8	4.3	4.7	4.8
Average velocity magnitude (ft/s)	1+17.39	2.7	3.3	3.5	3.5
	2+63.60	3.3	3.9	4.0	4.0
	3+34.57	3.6	5.2	5.4	5.4
	4+81.19	2.7	2.6	2.5	2.5
	5+67.26	2.5	3.1	3.0	3.0
	6+09.89	2.6	3.4	3.4	3.4
Average shear stress (lb/SF)	1+17.39	0.8	1.1	1.2	1.2
	2+63.60	1.2	1.4	1.3	1.3
	3+34.57	1.7	2.6	2.7	2.7
	4+81.19	1.0	0.8	0.7	0.7
	5+67.26	1.0	1.2	1.1	1.0
	6+09.89	1.1	1.4	1.4	1.4

Table 9: Existing-conditions velocities including floodplains at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	Main channel	ROB [a]
1+17.39	0.6	3.3	0.0
2+63.60	1.2	3.9	0.9
3+34.57	2.8	5.2	1.0
4+81.19	1.0	2.6	0.5
5+67.26	1.3	3.1	0.8
6+09.89	0.6	3.4	1.1

a. Properties of the LOB and ROB areas were calculated based on delineations established during draft preliminary hydraulic design modeling.

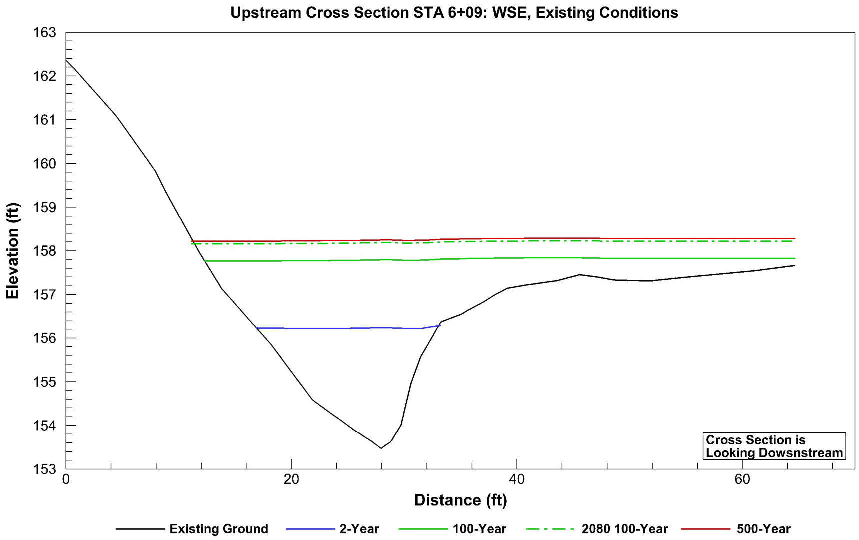

Figure 42: Typical upstream existing channel cross section

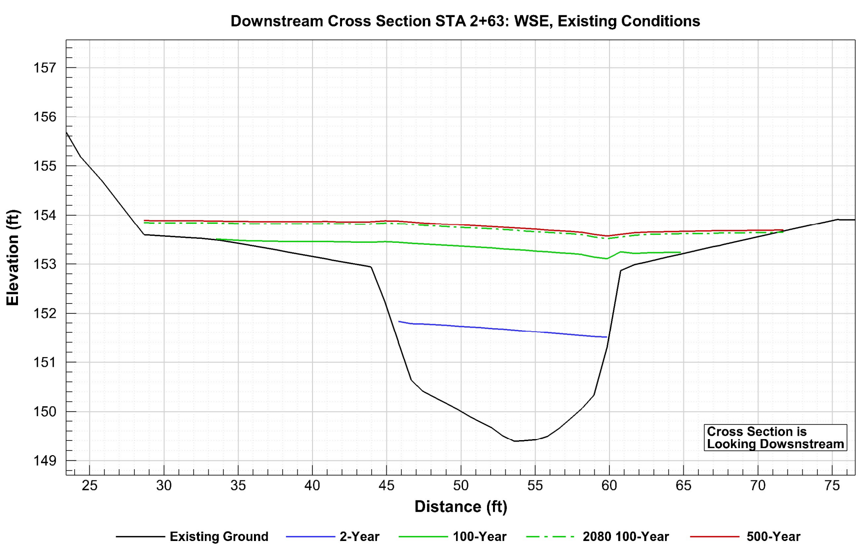

Figure 43: Typical downstream existing channel cross section

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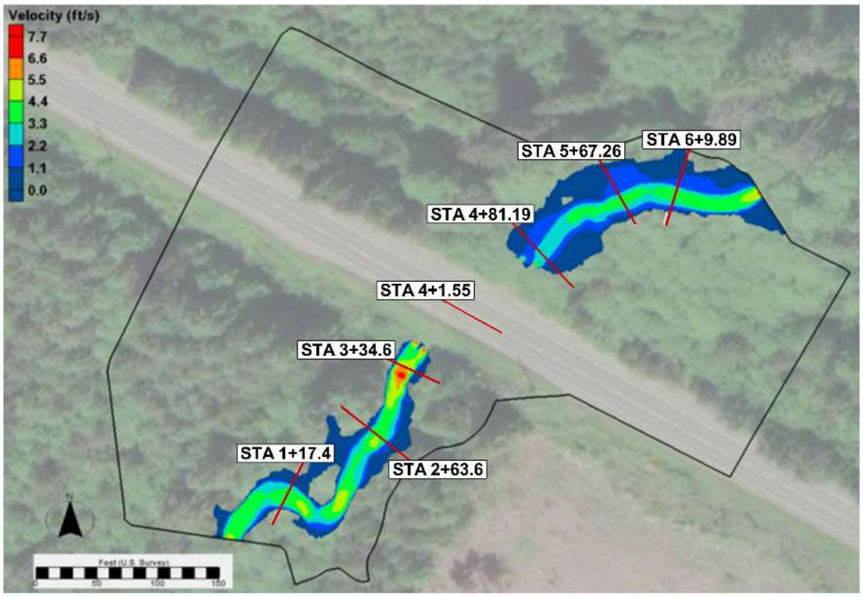

Figure 44: Existing conditions 100-year velocity map with cross-section locations

4.3 Natural Conditions Model Results

Locations of the cross sections used for reporting results for natural conditions simulations are the same as identified in Figure 39. Natural-conditions model results for the main channel are summarized for the upstream and downstream cross sections as well as the cross section within the proposed crossing in Table 10. Velocities are listed for main channel and left and right overbank (LOB, ROB) areas in Table 11. With the culvert removed and an assumed natural channel shape modeled through the crossing, the backwater effect is eliminated, resulting in depths similar to the reference reach (Figure 45). Upstream depths are slightly shallower than those in the downstream reach. Typical cross sections are depicted for upstream and downstream in Figures 45 and 46, respectively. All cross sections are depicted in Appendix C. Figure 47 shows the velocity contours for the natural conditions model with 100-year flow conditions. The upstream cross section shows an unconfined channel spreading flow into the floodplains at low flows. Velocities are similar along the length of the channel.

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Table 10

Table 10: Hydraulic results for natural conditions within the main channel

Hydraulic parameter	Cross section (STA)	2-year	100-year	100-year 2080	500-year
Average water surface elevation (ft)	1+17.39	150.7	152.2	152.6	152.6
	2+63.60	151.7	153.3	153.7	153.7
	3+34.57	152.6	153.9	154.3	154.3
	4+01.55 [a]	153.4	154.7	154.9	155.0
	4+81.19	154.1	155.4	155.7	155.7
	5+67.26	155.5	156.8	157.1	157.1
	6+09.89	156.0	157.4	157.7	157.8
Max water depth (ft)	1+17.39	2.7	4.3	4.7	4.7
	2+63.60	2.3	3.9	4.3	4.4
	3+34.57	2.4	3.8	4.1	4.1
	4+01.55 [a]	2.6	3.9	4.2	4.2
	4+81.19	2.7	3.9	4.2	4.2
	5+67.26	2.4	3.7	4.0	4.0
	6+09.89	2.6	4.0	4.3	4.3
Average velocity magnitude (ft/s)	1+17.39	2.7	3.3	3.5	3.5
	2+63.60	3.3	4.0	4.0	4.0
	3+34.57	3.4	4.4	4.4	4.4
	4+01.55 [a]	2.9	4.1	4.2	4.2
	4+81.19	2.9	3.9	4.1	4.1
	5+67.26	3.3	4.3	4.5	4.5
	6+09.89	3.0	3.9	4.1	4.2
Average shear stress (lb/ft²)	1+17.39	0.8	1.1	1.2	1.2
	2+63.60	1.2	1.4	1.4	1.4
	3+34.57	1.3	1.7	1.7	1.7
	4+01.55 [a]	1.0	1.5	1.5	1.5
	4+81.19	0.9	1.4	1.5	1.5
	5+67.26	1.7	2.4	2.6	2.6
	6+09.89	1.4	1.9	2.1	2.1

a. Cross section located at removed roadway embankment.

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Table 10: Natural conditions velocities including floodplains at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	Main ch.	ROB [a]
1+17.39	0.6	3.3	0.0
2+63.60	0.9	4.0	0.9
3+34.57	1.5	4.4	0.9
4+81.19	1.5	4.1	1.4
5+67.26	1.1	3.9	1.0
6+09.89	1.1	4.3	0.8

a. Properties of the LOB and ROB areas were calculated based on delineations established from survey cross sections

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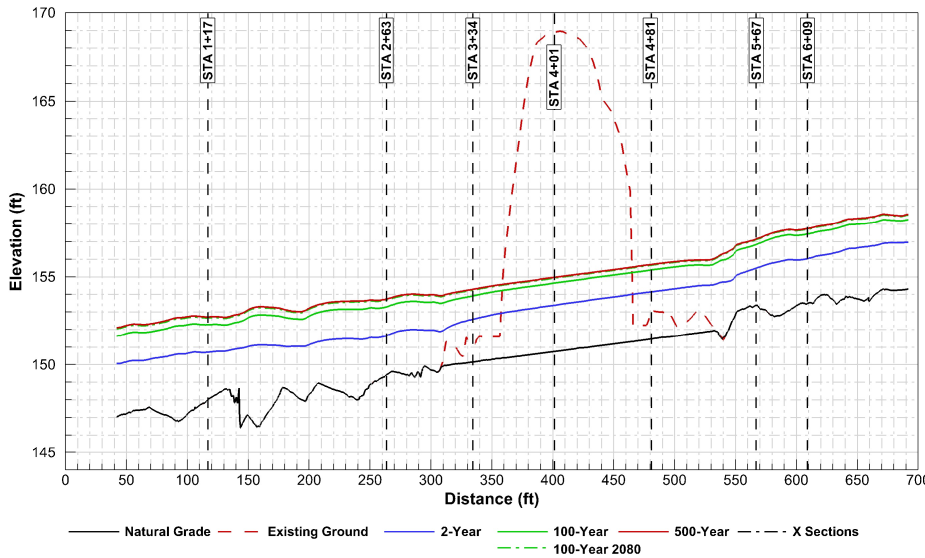

Figure 45: Natural-conditions water surface profiles

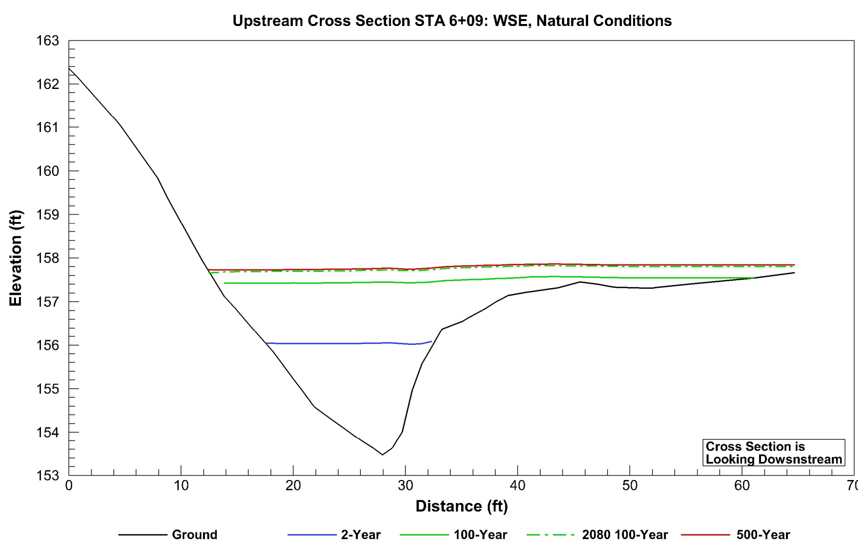

Figure 46: Typical upstream natural-conditions channel cross section

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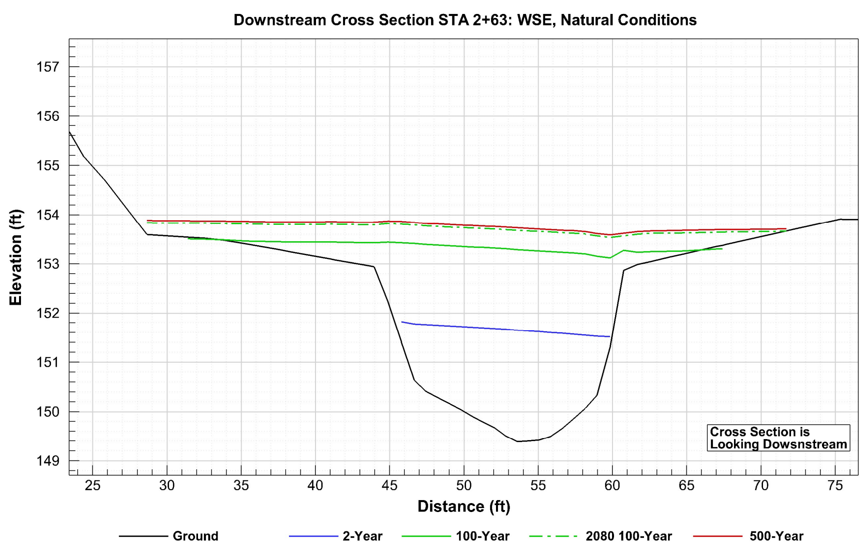

Figure 47: Typical downstream natural-conditions channel cross section

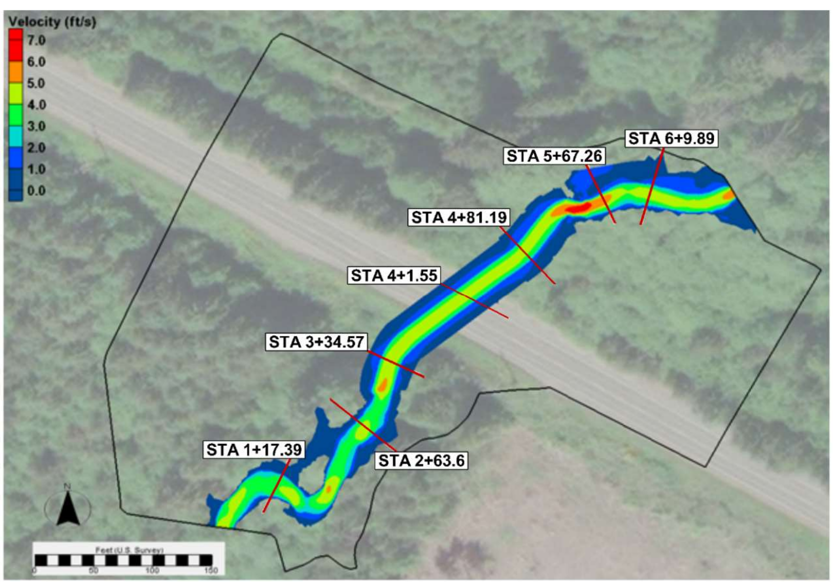

Figure 48: Natural conditions 100-year velocity map with cross-section locations

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4.4 Channel Design

This section describes the development of the proposed channel cross-section and layout design.

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4.4.1 *Floodplain Utilization Ratio*

The Floodplain Utilization Ratio (FUR) is defined as the flood-prone width (FPW) divided by the BFW. The FPW was calculated as the width at 100-year flood. A ratio under 3.0 is considered a confined channel and above 3.0 is considered an unconfined channel. The FUR was calculated assuming natural conditions, based on two cross-sections upstream of the culvert inlet location and three downstream of the outlet (Figure 49). Based on a BFW of 15 feet, an average FUR of 2.9 was calculated overall, indicating a confined site (Table 12). A stream simulation was therefore used as a starting point in the design development.

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Table 11: Flood-prone widths and floodplain utilization ratio results

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Parameter	Measurements (ft)					
	Upstream		Downstream			
	1	2	3	4	5	Average
FPW (measured from 100-year top width of model)	32.4	44.1	43	45	50.8	43
Associated FUR	2.2	2.9	2.9	3.0	3.4	2.9
Average FUR (upstream and downstream)	**2.6**		**3.1**			

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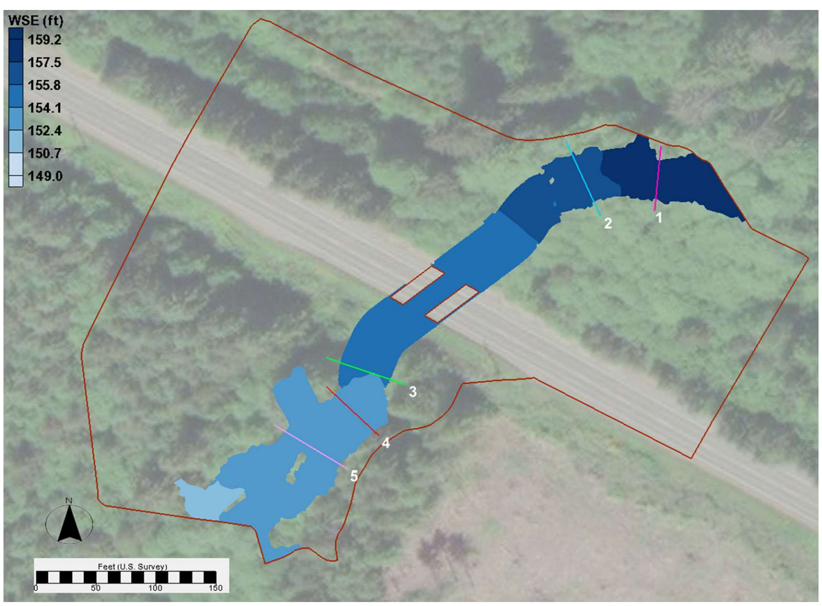

Figure 49: Locations of FPW measurements

4.4.2 *Channel Planform and Shape*

The WCDG prefers in a stream simulation design that the channel planform and shape mimic conditions within a reference reach (Barnard et al. 2013). The proposed channel cross-section shape accordingly emulates WSDOT's typical reference channel-based design (Figure 50), with the relative location of the thalweg across the section varying depending on whether the channel is straight or curving. A meandering planform is proposed within the replacement structure to increase total roughness within the culvert and accordingly reduce velocities, and to provide greater habitat complexity.

The bottom cross-section shape of the reference-based channel has a bottom side slope of 5 horizontal (H):1 vertical (V) between the thalweg and bank toes, 2H:1V streambank slopes, and an overbank terrace at roughly a 10H:1V slope to create a channel similar to the observed existing channel shape. It is expected that the bottom shape will continue to adjust naturally during high water, where the proposed shape provides a reasonable starting point for subsequent channel shape evolution and bank stability will be provided via bioengineering design. Overall, the proposed design cross-section shape approximates reference reach conditions (Figure 51).

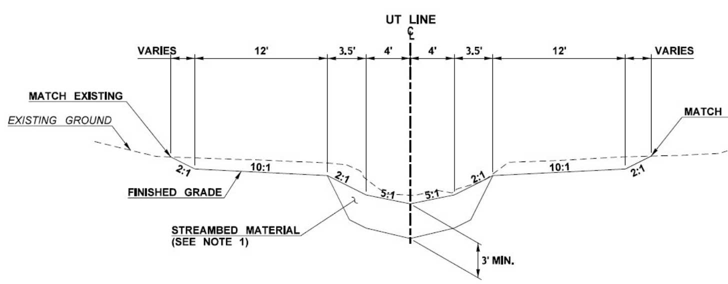

Figure 50: Design cross section

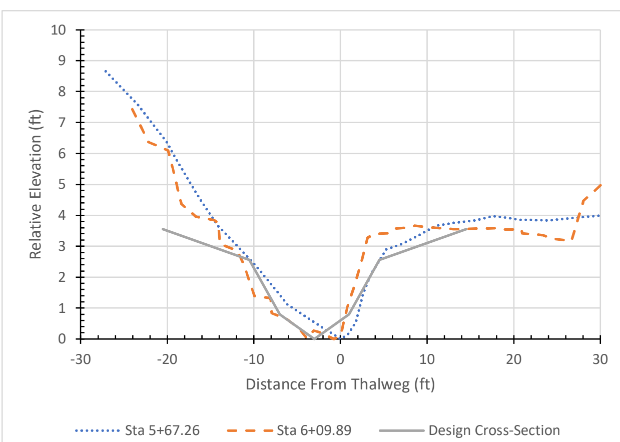

Figure 51: Proposed cross section superimposed on existing reference reach cross sections

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Outside of the replacement structure, the proposed channel cross-section profile generally follows WSDOT's typical reference channel-based design (Figure 50), with the relative location of the thalweg across the section varying depending on whether the channel is straight or curving. The proposed channel shape includes 5 horizontal (H):1 vertical (V) slopes between the toes and 2H:1V bank slopes to create a channel similar to the observed channel shape, and 20H:1V slopes to simulate the existing floodplains and connect the proposed grading to the existing surface (Figure 51). . ¶
As discussed above, however, the proposed design cross section within the structure will reflect the constraint posed by side slope stability of an unarmored, non-cohesive streambed, and the geomorphic observation that gravel supply rates to the culvert are expected to be lower than transport capacity. An over-steepened side slope with too small a substrate size distribution can be expected to regrade and flatten out during the first winter high flow(s) if a mobile bed is specified, and lose material to downstream that may then subsequently plug the channel there. For example, for the design stream slope of 0.009 and a streambed blend with a D_{50} = 2.0 inches, which is nearly three times the typical gravel patch substrate D_{50} (see Table 4), a 10H:1V side slope is predicted to be unstable during the 2080 100-year flood (Appendix D). The 2H:1V side slope in the reference-based channel profile will accordingly not stay in place without a stabilizing influence such as can be provided by vegetation, or by a large sized substrate. A larger D_{50} = 7.5 inches is associated with a stable 2H:1V side slope, but constructing the channel within the culvert using only this size material will equate to designing a roughened channel that is fixed in place, and it is likely that the side slope may still erode and regrade over time as debris and wildlife pass through the culvert.¶

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Bioengineering methods can be implemented towards long term stability of the channel cross-section shape and planform outside the culvert. This is not necessarily the case for under replacement structures that are not long, high bridges, however, as is the case for this site where bank stabilizing vegetation typically will not grow and use of large woody material presents special constructability and maintenance problems. Except for very slow, low gradient channels, it is not possible to preserve a steep side slope without vegetation or specifying a particle size that is markedly larger than that typically specified for an alluvial, mobile streambed and is stable under all flows. For the project stream's gradient, side slope stability equations predict that gravel and cobble substrates will mobilize readily unless the cross-section is relatively flat (see Appendix D). Indeed, this is a primary reason why the shapes of constructed stream simulation designs using gravel and cobble tend to wash out and flatten within the first winter season of high flows. In the case of the project stream, calculations based on the hydraulic model predictions of shear stress and velocity during the 100-year flood peak indicate that while a flat bottom cross-section is stable when the streambed grain size distribution approximates the sieve sample in Table 4, a 2H:1V side slope is not (see Section 5).

However, the stream simulation design methodology as stipulated in WAC 220-660-190 is based on emulating a mobile bed reference channel morphology and substrate within the structure as well as outside, irrespective of future evolution of the channel cross-section profile. Given that vegetative stabilization is not feasible for this site, and measures to fix the bed in place are inconsistent with the stream simulation design approach, an alternate method is needed to counter flattening of the bed and preserve a meander morphology. Accordingly, the proposed design consists of a cobble surface armor layer placed on top of meander bars. The cobble is sized to become partially mobile around the 100-year flood level so that material can adjust as needed yet remain within the culvert with the goal of preserving a meandering planform. The design rationale for specifying the grain size distribution of the cobble armor layer is described in greater detail Section 5. In general, the following considerations influenced design of the meander bars:

- The meander bars should be composed of a surface layer consisting of coarser cobble material that can self-organize into a stable, natural arrangement under a 100-year flood flow to avoid flattening out of the cross-section profile. Specific criteria include:
    - The grain size distribution of the material should reflect a critical dimensionless shear stress between 0.03 and 0.06, and closer to 0.03 in order to maintain a riffle form (e.g., Pasternack and Brown 2013; see Section 5.1).
    - The thickness of the surface layer should be at least twice the D_{90} of the cobble material, which is the general expected disturbance depth of a coarse bedded surface layer that is disturbed by mobilizing flows (cf. Wilcock et al. 1996; DeVries 2002). It is not necessary to extend this material all the way down to the bottom of the streambed fill because it is designed to adjust with streambed regrading but generally remain at the same location within the culvert. However, in cases where an additional safety factor is desired, the layer can extend down to the depth of the constructed thalweg.
- The design goal for spacing of the bars should reflect a maximum head drop over a naturally formed riffle, rather than emulating a classic geomorphic pool-riffle spacing criterion, given the meander bars are intended to be effectively stable. To reduce the potential for re-grading to adversely affect upstream swimming ability, the head drop between bar centerlines (across the

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channel) should be below typical criteria for juvenile salmonids to accommodate upstream movements of other native fish species. For this site, a head drop of 3 inches between bar apices was selected based on professional judgment, where the drop is expected to be across a naturally formed riffle after the streambed is reworked by floods, assuming worst case regrading occurs such that the gradient of the streambed between bar apices becomes flatter.

- The bar material should not protrude above the design surface, where the intervening material is designed to be in flush with the edge of the bar material and is sized to be stable on the prevailing stream gradient and side slope.
- Additionally, stable habitat boulders (typically 2-man or larger; WSDOT specification 9-03.11(4)) can be placed embedded into the streambed surface to increase channel roughness, which helps slow velocities within the structure and provide hydraulic sheltering for fish during high flows.

The corresponding proposed design is depicted schematically in Figure 52.

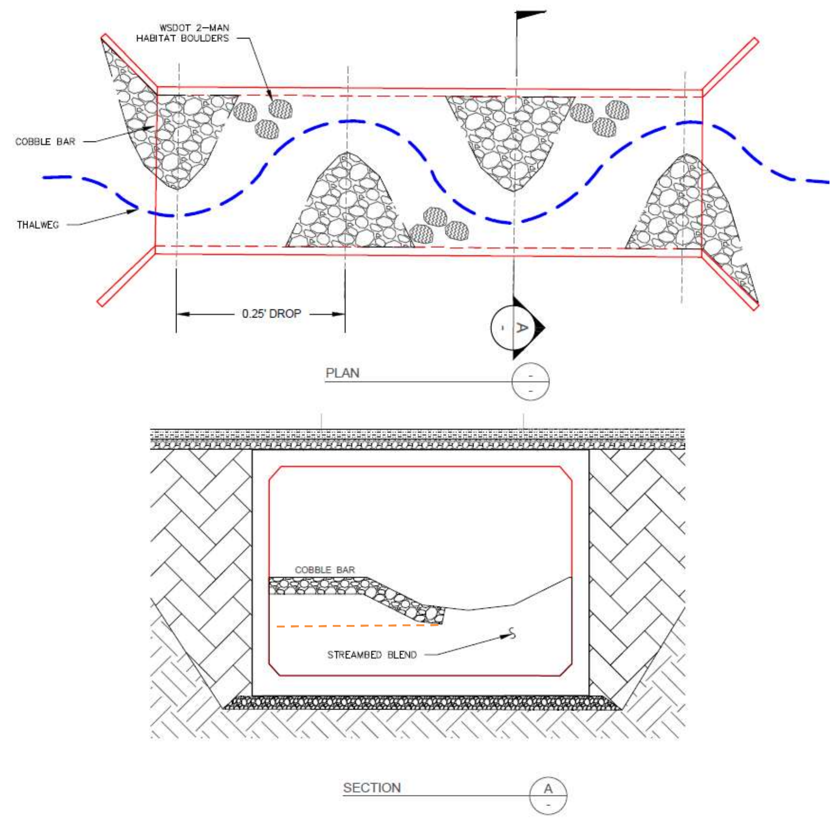

Figure 52: Schematic of proposed planform (top) and cross-section (bottom) layout inside the culvert. If there is concern of future loss of bar material to downstream, the thickness of the cobble layer can be increased to the dashed line.

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As can be inferred from above, there is some flexibility in the design of the cross-section profile side slope, but this reflects the constraint posed by substrate size. We have found a 7H:1V side slope to generally work well in that it is associated with a passage lane for juvenile salmonids that is approximately 2 inches deep at a flow of 1 cfs, and only a slightly greater D_{50} (2.2 inches) than the stable streambed mix for a flat slope (2.0 inches) is required for stability during the 100-year flood peak. For simplicity, however, a 5H:1V side slope was settled on in Stream Team design discussions because it is consistent with the bottom side slope outside of the culvert, and thus is simpler to warp the constructed surface between the culvert and reference-based streambed channel fill. This side slope requires a 2.35 inch D_{50} for stability and can be constructed using 6 inch cobble following WSDOT standard specification 9-03.11(2) (Appendix D). ¶
The prismatic option is simpler to construct than a meandering thalweg, but can be associated with faster flows because flow resistance is provided only by grain size. The meandering option can include an additive flow resistance component in the form of alternating bars that dissipate some of the stream energy as bedforms, and can be implemented via the following proposed design considerations:¶
The alternating bars should be composed of . . . generally immobile material. Based on calculations in section 5 and Appendix D, the bars should be composed of 6 inch minus cobbles following WSDOT's standard specification 9-03.11(2).¶
Material between and around the bars and outside the replacement culvert can be composed of smaller grain sizes. Given the relatively large gravel supply, the material placed can resemble the native gravel GSD in Table 4, which is approximated by 4-inch cobble following WSDOT's standard specification 9-03.11(2) (Appendix D).¶
Spacing of the bars should reflect a maximum head drop design goal rather than emulation of a classic geomorphic pool-riffle spacing criterion, given the bars are to be effectively stable. To reduce the potential for re-grading to adversely affect upstream swimming ability, the head drop between bar centerlines (across the channel) should be below typical criteria. For this site, a head drop of 3 inches was selected based on professional judgment. ¶
When the bar material is sized appropriately, the bars may deform somewhat, but as long as they stay in their general location to ensure that the head drop does not become excessive. ¶
The bar material should not protrude above the design surface, where the intervening material is designed to be in flush with the edge of the bar material and is sized to be stable on the prevailing stream gradient assuming negligible side slope.¶ ... [2]

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4.4.3 *Channel Alignment*

The proposed project alignment follows the existing alignment. There were no artificial constraints on the channel alignment. The proposed channel alignment is illustrated in design drawings provided in Appendix E.

4.4.4 *Channel Gradient*

The channel will be regraded starting approximately 45 feet downstream of the existing culvert outlet, starting above the natural log step, and extending to roughly 60 feet upstream of the existing culvert inlets. It was agreed during the July 14, 2021 field visit between WSDOT and the Co-Managers that the natural step could be left in place, but that the grading should accommodate potential future degradation if the step goes away naturally. To that end, the grading will tie into the bottom of the scour pool below the constructed log weir. The entire channel grading extent, including within the proposed structure, is 220 feet long. The WCDG recommends that the proposed culvert bed gradient not be more than 25 percent steeper than the existing stream gradient upstream of the crossing (WCDG Equation 3.1). The proposed channel gradient is approximately 0.9 percent, and the reference reach gradient is approximately 0.97 percent (Figure 22), resulting in a slope ratio of 0.9. The proposed slope ratio is under the WCDG's recommended maximum value of 1.25 (Barnard et al. 2013). As discussed in section 2.8.4, additional regrading may be expected in the future. The Co-Managers concluded during the July 14, 2021 field visit that natural regrading would be considered acceptable.

4.5 Design Methodology

The proposed fish passage design was developed using the 2013 *Water Crossing Design Guidelines* (Barnard et al. 2013) and the WSDOT *Hydraulics Manual* (WSDOT 2019). Using the guidance in these two documents, the stream simulation design method was determined to be appropriate at this crossing because the average FUR was calculated to be close to 3.0. Two additional requirements for the stream simulation method were also met: the BFW in the reach averaged 15 feet, and the proposed channel gradient met the slope ratio.

4.6 Future Conditions: Proposed 24-Foot Minimum Hydraulic Opening

The determination of the proposed minimum hydraulic opening width is described in section 4.7. A 24 feet wide opening was modeled as an open channel with a 15 feet BFW channel and floodplain, with vertical side walls. The channel cross-section profile design proposed above in section 4.4 for within the structure awaits approval, and so for the present simulations, the general cross-section profile depicted in Figure 50 was simulated inside the culvert. The resulting hydraulic predictions were used in the analyses described in section 4.4 to yield conservative design parameters for freeboard and substrate sizing, and for guiding final design of a persistent cross-section profile within the culvert absent bank-stabilizing vegetation.

Hydraulic simulation results are summarized for proposed conditions at cross-sections upstream, downstream, and within the proposed crossing in Table 12. Locations of the cross sections used for reporting results for proposed conditions simulations are the same as identified in Figure 39. Average velocities across the main channel, LOB, and ROB of each cross section for the 100-year flow are

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summarized in Table 13. The larger proposed structure reduced water surface elevations upstream and has similar results to the natural-conditions model (Figure 53). The 100-year water surface elevation at the upstream cross section (STA 4+81) was predicted to decrease by 0.9 feet from existing conditions. A cross section showing WSEL in the proposed structure is shown in Figure 54.

Velocities upstream are predicted to increase slightly compared to existing conditions because of the reduced backwater. Maps of the predicted velocity fields for the present day and 2080 100-year flow conditions are depicted in Figures 55 and 56, respectively.

Table 12: Hydraulic results for proposed conditions within the main channel

Hydraulic parameter	Cross section (STA)	2-year	100-year	2080 100-year	500-year
Average water surface elevation (ft)	1+17.39	150.7	152.2	152.6	152.6
	2+63.60	151.7	153.4	153.7	153.8
	3+34.57	152.6	154	154.3	154.4
	4+01.55*	153.3	154.5	154.8	154.8
	4+81.19	154.1	155.3	155.6	155.7
	5+67.26	155.5	156.8	157.1	157.1
	6+09.89	156.0	157.4	157.7	157.7
Max water depth (ft)	1+17.39	2.7	4.3	4.7	4.7
	2+63.60	2.3	4.0	4.3	4.4
	3+34.57	2.5	3.9	4.2	4.2
	4+01.55*	2.5	3.8	4.0	4.1
	4+81.19	2.6	3.9	4.2	4.2
	5+67.26	2.4	3.7	4.0	4.0
	6+09.89	2.6	4.0	4.3	4.3
Average velocity magnitude (ft/s)	1+17.39	2.7	3.3	3.5	3.5
	2+63.60	3.6	4.1	4.2	4.2
	3+34.57	3.4	4.2	4.3	4.3
	4+01.55*	3.2	4.6	4.9	5.0
	4+81.19	3.0	4.1	4.2	4.2
	5+67.26	3.4	4.3	4.5	4.5
	6+09.89	3.2	3.9	4.1	4.2
Average shear stress (lb/ft²)	1+17.39	0.8	1.1	1.2	1.2
	2+63.60	1.4	1.6	1.5	1.5
	3+34.57	1.3	1.6	1.6	1.6
	4+01.55*	0.4	0.7	0.8	0.8
	4+81.19	1.0	1.5	1.6	1.6
	5+67.26	1.7	2.5	2.6	2.6
	6+09.89	1.5	1.9	2.1	2.1

* - Cross section located in structure

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Table 13: Proposed conditions velocity predictions at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	Main ch.	ROB [a]
1+17.39	0.7	3.3	NA
2+63.60	1.3	4.1	1.0
3+34.57	1.5	4.2	1.0
4+01.55	1.7	4.6	1.9
4+81.19	1.2	4.1	1.1
5+67.26	1.1	4.3	0.8
6+09.89	0.5	3.9	1.5

a. Properties of the LOB and ROB areas were calculated based on delineations established during draft preliminary hydraulic design modeling.

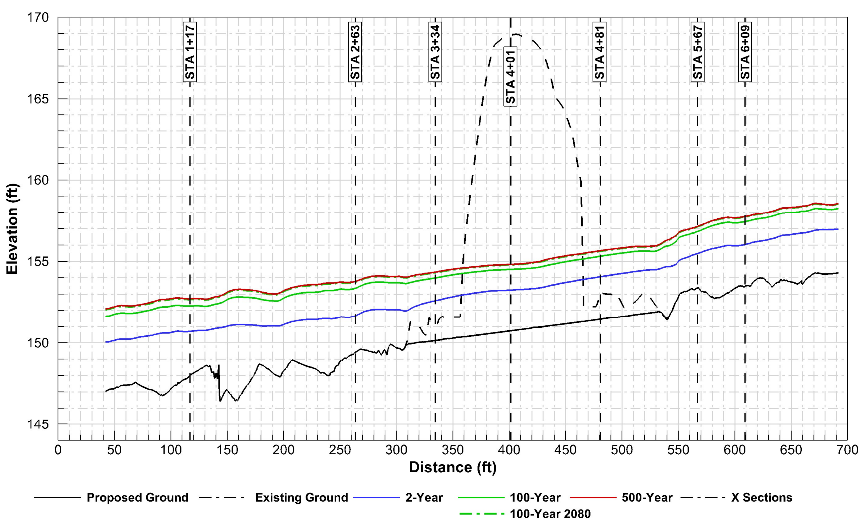

Figure 53: Proposed-conditions water surface profiles

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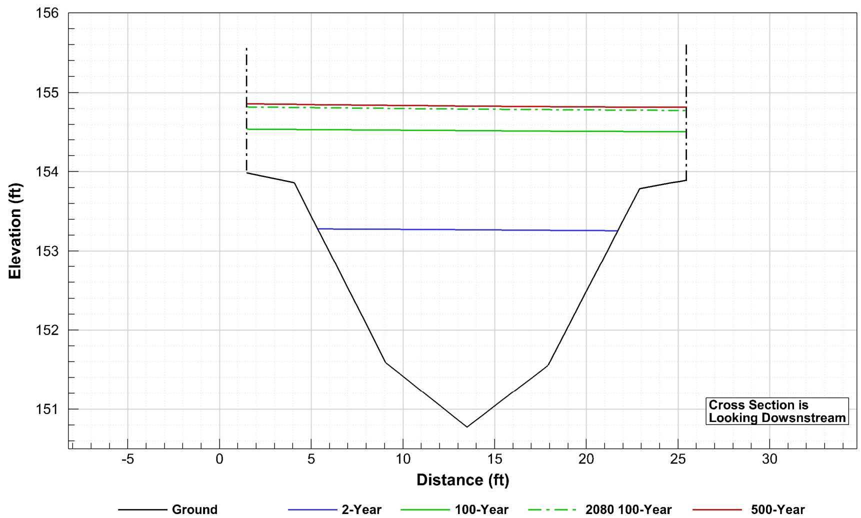

Figure 54: Section through proposed structure (STA 4+01)

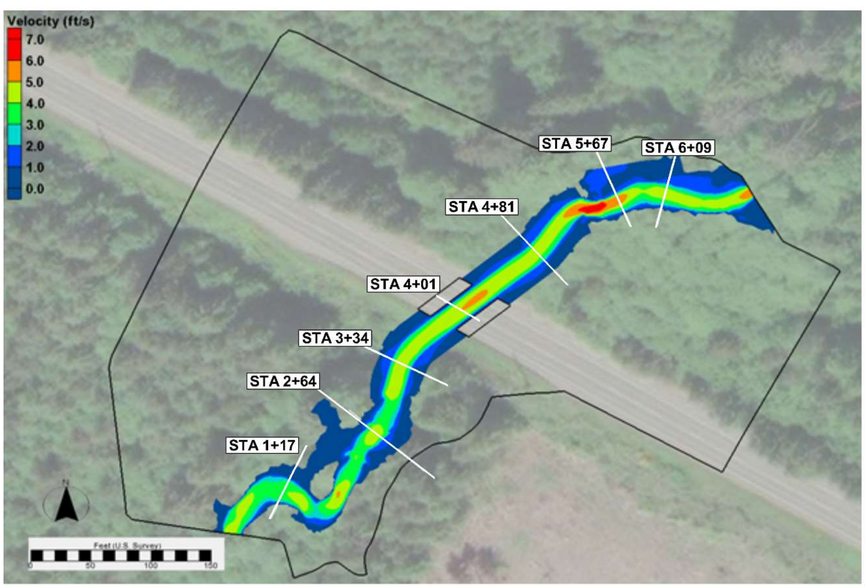

Figure 55: Proposed-conditions 100-year velocity map

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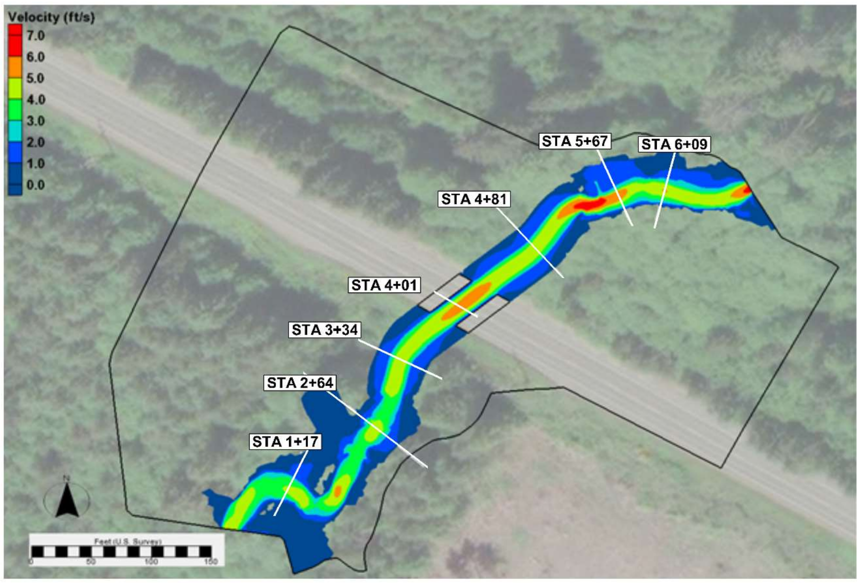

Figure 56: Proposed-conditions 2080 predicted 100-year velocity map

4.7 Water Crossing Design

Water crossing design parameters include structure type, minimum hydraulic opening width and length, and freeboard requirements.

4.7.1 *Structure Type*

A structure type has not been resolved at present and will be determined at later project phases.

4.7.2 *Minimum Hydraulic Opening Width and Length*

The hydraulic opening is defined as the width perpendicular to the creek beneath the proposed structure that is necessary to convey the design flow and allow for natural geomorphic processes. The hydraulic opening assumes vertical walls at the edge of the minimum hydraulic opening width unless otherwise specified. The starting point for determining the design width of all WSDOT structures is Equation 3.2 of the WCDG (Barnard et al. 2013), rounded up to the nearest whole foot. For this crossing, a minimum hydraulic opening of 20 feet was determined to be the minimum starting point based on a BFW of 15 feet per concurrence of the co-managers and the Stream Team as outlined in Section 2.8.2. This is generally wider than the incised channel downstream. In addition, a 24 feet wide structure for wildlife connectivity was evaluated.

The present day 100-year and projected 2080 100-year peak flood magnitudes were evaluated for the proposed conditions to evaluate predicted velocities in both a 24 feet hydraulic opening width proposed for wildlife connectivity, and a 20 feet wide opening resulting from Equation 3.2 of the WCDG. There is

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no substantive difference in predicted water surface elevation (WSEL) profiles or main channel velocities for the two widths (Figure 57; Table 14). The structure therefore does not need to be widened any further than that proposed for wildlife connectivity.

The proposed length is approximately 105 feet, slightly shorter than the existing culverts.

Table 14: Predicted main channel velocities within 24 feet and 20 feet wide structures

Simulation	Hydraulic Opening Width (ft)	Proposed 100-Year Velocity (ft/s)
100-year	20	4.6
2080 100-year	20	4.9
100-year	24	4.6
2080 100-year	24	4.9

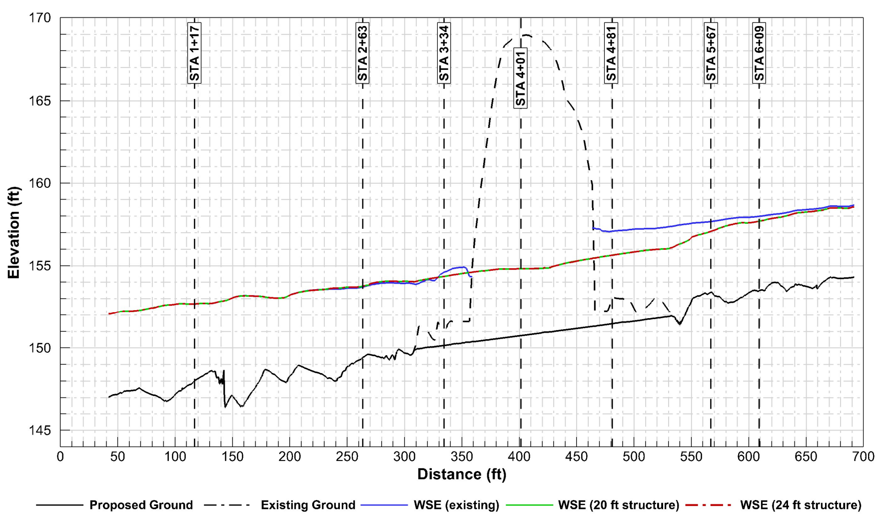

Figure 57: Existing and proposed 100-year water surface profile comparison for 20- and 24-feet wide structures

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Based on the factors described above, a minimum hydraulic opening of 20 feet can be considered was determined to be sufficient to protect fish passage and allow for natural processes to occur under current and projected future flood conditions. However, taking a conservative approach, the width was increased to 24 feet. Table 15 shows the velocity ratios for a structure with an hydraulic opening of 24 feet. The velocity ratio was calculated by dividing the average channel velocity through the structure by the average channel velocity at the reference reach. The reference reach velocity was calculated as the average of velocities at 4 equally spaced cross sections at the reference reach. The proposed length is approximately 105 feet, slightly shorter than existing. As shown in Table 15, the velocity ratio is 1.1 for both the present day 100-year and projected 2080 100-year peak flow scenarios.

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4.7.3 ***Freeboard***

Freeboard is necessary to allow the free passage of debris expected to be encountered. The WCDG generally suggests a minimum 2-feet clearance above the 100-year WSEL for streams with a BFW between 8-15 feet to adequately pass debris (Barnard et al. 2013). WSDOT has determined that structures 20 feet and wider will require a minimum freeboard of 3 feet. WSDOT also desires a minimum vertical clearance between the culvert soffit and the streambed thalweg for maintenance equal to 6 feet where possible. As an additional consideration, this site has been identified as a wildlife connectivity crossing (see section 2.6), which may require a different minimum freeboard. WSDOT is incorporating climate resilience in freeboard, where practicable, and so freeboard was evaluated at both the 100-year WSEL and the projected 2080 100-year WSEL. The hydraulic modeling indicates that the maintenance-based goal will not exceed the clearance required to meet the 3 feet hydraulic-based criterion associated with the proposed design when constructed (Table 15). Long-term aggradation risk is considered negligible at this location, whereas degradation risk is relatively high and could lead to increased freeboard in the future if the streambed regrades (see section 2.8.4).

Table 14: Parameters relevant to freeboard specification for proposed replacement structure

Parameter	2080 100-Year Coincident Flood Predictions	
	At Inlet	At Outlet
Thalweg elevation (ft)	151.33	150.39
Maximum WSEL (ft)	155.50	154.50
Minimum low chord elevation to provide 3 feet of freeboard (ft)	158.50	157.50
Minimum low chord elevation to provide 6 feet maintenance access (ft)	157.33	156.39
Recommended low chord elevation, without future aggradation (ft)	158.50	157.50

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4.7.3.1 Past Maintenance Records

WSDOT has indicated there have been no maintenance problems at this crossing.

4.7.3.2 Wood and Sediment Supply

The contributing basin is predominantly forested with medium to large trees present that are a potential source of LWM. Based upon the flow velocities, depths of flow, and BFW of the stream, the potential to transport LWM is low. As described in section 2.8.6, mobile wood pieces in the stream appear to be smaller than 9 inches in diameter and around 7 feet in length, and thus would be expected to clear easily under the proposed 20 feet wide structure with at least 2 feet of freeboard during the 100-year flood under future climate change projections. Larger, longer trees were seen to fall and remain in place farther upstream of the surveyed reach.

Based on the assessments of sediment character and vertical stability in Section 2.8, and the general geology described in section 2.2, the stream may have experienced episodic pulses of gravel passing through the project reach in association with historic timber harvest practices. With the adoption of more protective buffer zone width requirements, such episodes are expected to be less prominent in the future. Given the transport capacity of the stream and the proposed grade in line with upstream and downstream, gravel is not expected to build up in the vicinity of the culvert sufficiently to affect freeboard in the future.

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4.7.3.3 Flooding

The crossing is not in a mapped floodplain, as discussed in Section 2.3. There is a mapped floodplain beginning approximately 400 feet downstream of the crossing, reflecting backwatering from Big Creek. The floodplain is not expected to be affected by this project. As demonstrated with the proposed model, average water depths are unaffected at the two most downstream cross sections. The proposed structure will reduce upstream water surface elevations and flooding extents. Flooding impacts are discussed in more detail in Section 6.

4.7.3.4 Future Corridor Plans

There are currently no long-term plans to improve U.S. 101 through this corridor.

5 Streambed Design

The streambed design considered the local characteristic grain size distribution (GSD) of gravel characterized by a pebble count and the bulk sieve sample, standard streambed stability calculations for the proposed channel longitudinal and cross-section profile grading, and requirements of WAC 220-660-190. Two GSDs were developed, one for the streambed mix, and the second for a cobble armor surface on proposed meander bars within the replacement structure. In addition, large woody material is proposed to be placed on and over the streambed to provide instream habitat complexity and overhead cover for fish. These two elements of the design are described in separate sections below.

5.1 Bed Material

Where neither of the other two alternative approaches identified in Section 1.0 are indicated for implementation, the injunction requires that the design follow the stream simulation methodology as described in the WAC and WCDG (Barnard et al. 2013). WAC 220-660-190 stipulates that "The median particle size of sediment placed inside the stream-simulation culvert must be approximately twenty percent of the median particle size found in a reference reach of the same stream. The department [WDFW] may approve exceptions if the proposed alternative sediment is appropriate for the circumstances." WSDOT has decided that exceptions should be avoided where possible. In general, what this means is that the streambed substrate grain size distribution is required to have a D_{50} within +/- 20 percent of the native reference substrate. This requirement is not strictly possible to meet at this site, because the reference reach substrate consists primarily of fine material that would not be expected to remain stable if placed within the culvert. There are isolated patches of gravel, so an exception is recommended for this site where the streambed design is instead based on the reference gravel patch grain size distribution with an assessment of risks associated with potential streambed instability. Relevant calculations are presented in Appendix D and their implications to the design are summarized below.

The evaluation of streambed instability risk focused first on determining the critical D_{50} for a partially mobile streambed mix at the 2- and 100-year flood peaks, and for meander bars at the 100-year flood peak with a surface GSD on the verge of mobility. Intermittent transport generally occurs when the dimensionless ("Shields") shear stress is less than 0.03 in value, and partial mobility falls with the range 0.03-0.06 (Lisle et al. 2000; Wilcock et al. 1996; Pasternack and Brown 2013). To emulate a partially adjustable streambed for this design, the critical dimensionless shear stress based on the median (D_{50}) particle size was set to 0.045 for the streambed mix, and 0.03 for the meander bar surfaces.

The SRH-2D model outputs an estimate of shear stress, but the result is based on a 2-D vector adaptation of the uniform flow, wide channel 1-D approximation, and accordingly is a significant over-estimate compared with that derived from velocity profiles (Wilcock 1996; Pasternack et al. 2006; DeVries et al. 2014). Pasternack and Brown (2013) determined that the type of equation used more closely matches the velocity profile-derived estimate when the velocity is evaluated near the bed. However, SRH-2D calculates a mean column velocity, but that can be used to estimate near bed shear velocity and thus shear stress. Two different velocity relations based on the rough form of the law of the

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wall were evaluated accordingly, and they gave comparable order of magnitude predictions of shear stress (Richards 1982; Pasternack and Brown 2013). The larger of the two estimates was used to size streambed substrates accordingly using Shields' equation (see Appendix D). For specifying the overall grain size distribution, guidelines were adopted from Barnard et al. (2013) and USACE (1994).

Following the above approach, the critical Shields stress = 0.045 criterion corresponds approximately to a critical D_{50} = 0.4 inches at the 2-year flood, and 0.85 inches at the 2080 100-year flood. Correspondingly, a streambed mix emulating the native gravel GSD in Table 4 with a D_{50} = 0.7 inches would be expected to be stable at the 2-year flood, but it would be mobilized during the 100-year flood peak. The associated Shields stress at the 100-year flood peak is calculated to be 0.058, which indicates that the native gravel GSD may be on the verge of full mobility, although the modified Shields approach (USFS 2008) predicts that the native gravel D_{84} size should be generally stable.

The geomorphic reach conditions are such that the supply rate of native gravel from upstream is relatively high, but there are still some risks inherent to bed stability and overall grade, however. Given the predicted mobility of the native D_{50} at the 100-year flood, a small degree of coarsening could be expected inside the structure. In addition, as discussed in Section 2.8.4, extensive incision of the bed should be expected within the regraded reach. To reduce the extent to which both processes occur, and to help maintain a cross-section shape that is not flat, a slightly coarser mix that is partially mobile at the 100-year flood is recommended. The corresponding recommended GSD has a D_{50} = 0.85 inches, which also approximately meets the WAC's +/- 20 percent regulatory requirement. The coarsest tail of the recommended GSD following WCDG guidelines is 5.3 inches, which is generally coarser than other guidelines for substrate stability (e.g., USACE 1994). The 4-inch cobble specification is more than three times the D_{50} value and was accordingly specified to facilitate a simpler mixing ratio involving just two standard streambed specifications.

Construction of meander bars with a coarser cobble surface would help further mitigate the above risks. For ensuring the general persistence of meander bars within the replacement structure and reducing the potential for flattening and regrading of the streambed profiles, the specified cobble surface GSD should be stable on a side slope that is intermediate to 2H:1V and a flat cross-section profile. A 5H:1V side slope was selected as a design criterion because it matches the design bottom slope of the reference cross-section depicted in Figure 50. Equations for side slope stability at the 100-year flood peak were applied from Mooney et al. (2007). A D_{50} = 1.5 inches is estimated to be required for a stable 5H:1V side slope at the 100-year flood peak, with a D_{max} of approximately 9 inches following the WCDG. This distribution brackets the lower range of the GSD for WSDOT specification 9-01.11(2) 6-inch cobble. Analogous to the streambed mix, the 6-inch cobble specification is more than three times the D_{50} value and accordingly should support persistence of a meander bar form within the replacement structure.

A comparison of the observed, stable, and proposed streambed material GSDs is provided in Table 16. These GSDs meet the Fuller-Thompson criterion for reducing subsurface flow potential. The values reflect designing for the worst-case tributary only scenario and absence of roughness elements inside the replacement structure.

To achieve the stream simulation design mix D_{50}=1.5 inches, materials meeting WSDOT's specifications for streambed sediment [9-03.11(1)] and 4-inch cobble [9-03.11(2)] should be mixed in roughly a 5:4

proportion. However, because actual mixes noted as meeting WSDOT specifications at pit sources can be highly variable in their composition, this ratio must be verified by sieving at the source and adjusted as needed to reflect materials that are actually available at the time of construction. WSDOT's specifications for streambed and 6-inch cobble [9-03.11(2)] can be used for the meander bar cobble surface material.

Table 156: Comparison of observed and proposed streambed material

Sediment size	Observed Diameter (in)	Proposed Streambed Design Diameter (in)	Meander Bar Design Diameter (in)
D_{16}	0.3	0.1	0.2
D_{50}	0.7	0.85	1.5
D_{84}	1.4	2.1	3.7
D_{90}	1.8	2.6	4.4
D_{100}	4.0	4.0	6.0

5.2 Channel Complexity

To mimic the natural riverine environment and promote the formation of habitat, the design incorporated placement of key LWM pieces within and across the channel and floodplain. Placement will generally mimic tree fall and embedded wood pieces observed upstream and downstream of the crossing. The design accordingly involves addition of LWM to enhance and promote channel complexity for fish habitat. In addition, the design involves placement of LWM as a means to trap gravel and counter the potential for further channel degradation. This will be accomplished by placing a large number of LWM pieces, especially downstream, to increase hydraulic roughness and energy dissipation, which will also help reduce velocities upstream within the replacement culvert.

5.2.1 *Design Concept*

The total number of key pieces was determined in consideration of criteria presented in Fox and Bolton (2007) and Chapter 10 of the *Hydraulics Manual* (WSDOT 2019), in which WSDOT's recommended key piece density for the project site is 3.4 key pieces and 39.48 cubic yards of volume per 100 feet of channel. A key piece is defined as having a minimum volume of 1.31 cubic yards, which corresponds roughly to a 30 feet long log that has a diameter at breast height (DBH) of 15 inches. WSDOT has established a design goal for this project where the Fox and Bolton (2007) criteria are to be calculated for the total regrade reach length including the culvert, but the pieces of wood are to be distributed outside of the culvert. For the proposed total regrade length of 220 feet, the design criteria for this reach are seven key pieces with a total LWM volume of 86.9 cubic yards (Appendix H). In small streams, the volume criterion may not always be practically achieved without completely filling the channel and placing a sizeable amount of wood outside of the 2-year flood extent, where smaller diameter logs can achieve the same biological and geomorphic functions. In this design, the primary goal was to exceed the density criterion to get closer to or even meet the volume criterion, while not overloading the stream channel outside of the culvert. Where feasible, wood can be added outside of the regrade extent with the condition that heavy equipment not disturb the channel and floodplain significantly.

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The substrate stability analysis summarized in section 4.5 and Appendix D indicates that the reference reach pebble count GSDs in Table 4 would not remain stable on the design 0.9% stream gradient during the 100-year flood without measures to reduce grain friction (i.e., shear stress on the grains). . However, the geomorphic reach conditions are such that the supply rate of native gravel from upstream appears to be sufficient to replace that material if placed within the constructed channel. Thus the proposed bed material gradation can be created using standard WSDOT specification material to mimic the native streambed material as quantified in the comparable pebble count and bulk surface samples. .A comparison of the observed and proposed streambed material size distribution is provided in Table 17. This GSD can be effectively replicated via approximately a 3.3:1 blend of WSDOT standard specifications for streambed sediment:4 inch cobble, respectively (Appendix D).¶
. . . . . As indicated in Section 4.5, the alternating bar substrate can be composed of 6 inch cobble following WSDOT standard specification 9-03.11(2) to achieve a stable cross-section slope within the culvert that should not flatten out substantially.

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A conceptual LWM layout has been developed for the project reach involving a mix of embedded and loose logs with rootwads (Figure 58). The conceptual layout proposes 27 key pieces in a 220-foot-long project reach (including the structure length), which is more than three times the number criterion, and exceeds the total number target of 25 pieces (Appendix H). There is space for this number of pieces at this site without significantly choking the channel and potentially causing an end run and significantly destabilizing constructed streambanks before revegetation is successful. This increased number of pieces in turn facilitates getting closer to the net volume target if pieces with sufficiently large diameter are not available (volumes calculated in Appendix H reflect more commonly available pieces). The mobility and stabilization of LWM will be analyzed in later phases of design. The design involves two log types:

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- Thirteen (13) embedded logs (Type 1) with rootwads to provide habitat and stabilize the constructed left streambank above and below the culvert; the logs downstream are intended to trap gravel and provide backwater roughness upstream in the culvert. The rootwad will be placed in the low flow channel with a preformed scour hole around it, and the butt end will be buried to sufficient length and depth that additional anchoring is not needed.
- Fourteen (14) loose, 30+ feet long logs with rootwads, and to the extent possible, with intact branches. Two will be placed with rootwad and trunk mostly in and over the channel (Type 2), eleven will be placed with rootwad in the channel and tip on the floodplain/adjacent slope (Type 3), and one will span the bankfull channel to promote scouring underneath (Type 4). The type 3 and 4 designs will involve self-ballasting and interlocking with existing trees for stability. The type 2 log will be kept in place by other logs abutting downstream of the rootwad.

The LWM pieces will be placed so they provide habitat features for fish, form pools, and refuge habitat under high flow conditions, and to promote increased roughness for gravel sorting and greater bed stability within the culvert. Wood stability and the need for anchoring will be assessed at the Final Hydraulic Design (FHD) level, and is likely to include the use of vertical posts to pin non-embedded, loose logs in place. Key pieces will be designed to be anchored by either suitable embedment length/depth, or interlocking with existing trees. To meet WSDOT's total LWM number target, nine (9) additional 12" or larger DBH trees with rootwads would be needed. These smaller pieces would need to be placed loose as directed work, or designed to be embedded in the banks, integrated with the installation of key pieces.

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Risk of fish stranding during summer flow conditions is minimal because proposed grading directs flow back to the main channel and does not promote isolated pools, and stream flow is perennial indicating continued contact with groundwater.

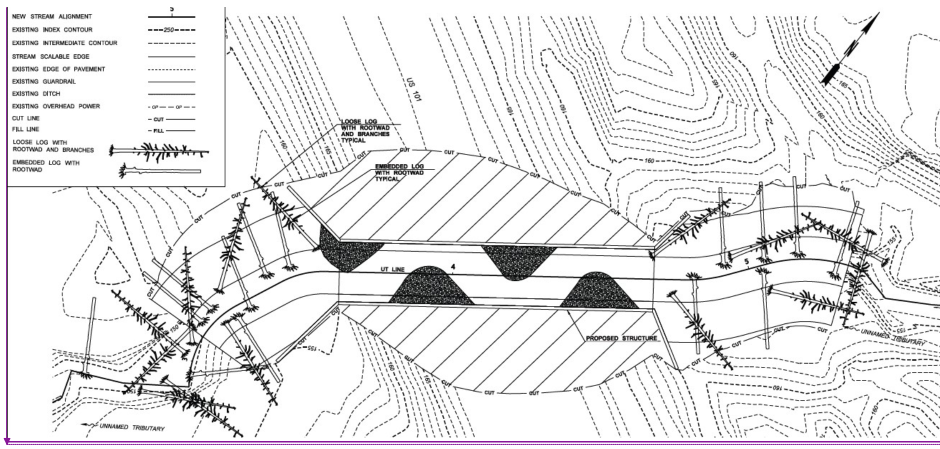

Figure 578: Conceptual layout of key LWM and alternating bars for habitat complexity

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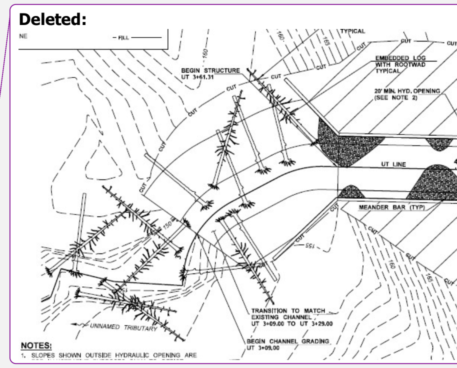

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6 Floodplain Changes

This project is not within a mapped FEMA floodplain. The pre-project and expected post-project conditions were evaluated to determine whether there would be a change in water surface elevation and floodplain storage.

6.1 Floodplain Storage

Floodplain storage is anticipated to be affected by the proposed structure. The installation of a larger hydraulic opening will greatly reduce the amount of backwater and associated peak flow attenuation that was being caused by the smaller, existing culverts. A comparison of pre- and post-project peak flow events was not quantified as the models were run with a steady flow rate specified at the upstream boundary of the model. No existing infrastructure is seen from aerial photography downstream of the crossing that would potentially be impacted.

6.2 Water Surface Elevations

Installation of the proposed structure would eliminate the backwater impacts just upstream of the existing culvert, resulting in a reduction in water surface elevation upstream. The water surface elevation is reduced by as much as 2.0 feet at the inlet of the existing culvert at the 100-year event as shown in Figures 59 and 60.

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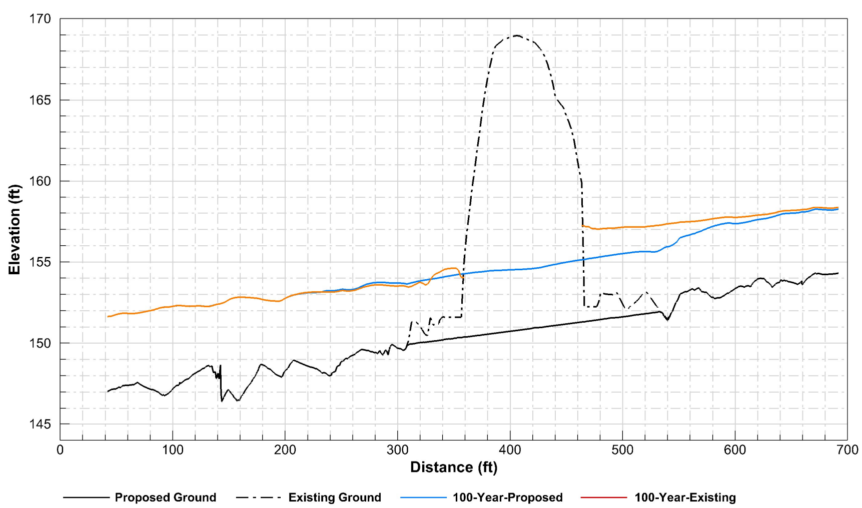

Figure 58: Existing and proposed 100-year water surface profile comparison

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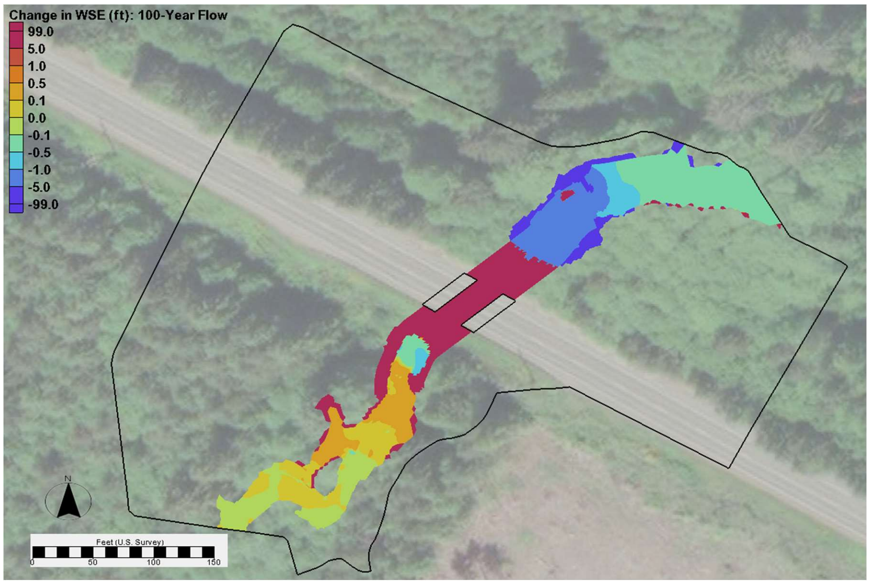

Figure 59: Water surface elevation change from existing to proposed conditions; purple denotes areas where a direct comparison is not possible

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7 Climate Resilience

WSDOT recognizes climate resilience as a component of the integrity of its structures and approaches the design of bridges and buried structures through a risk-based assessment. For bridges and buried structures, the largest risk to the structures will come from increases in flow. The goal of fish passage projects is to maintain natural channel processes through the life of the structure and maintain passability for all expected life stages and species in a system. At a minimum, climate change is addressed in all bridge, buried structure, and fish passage projects by providing a design in which the foundations or bottoms are not exposed during the 500-year flow event due to long-term degradation or scour. WSDOT also completes a hydraulic model for all water crossings on fish-bearing streams, regardless of design methodology, to ensure that the new structure is appropriately sized. If the velocities through the structure differ greatly from those found elsewhere in the reach, the structure width may be increased above what is required by Equation 3.2 in the WCDG.

General climate change predictions for the broader region are for increased rainfall intensity during winter months, with the caveat that there is great spatial variability in the projections that may preclude downscaling to the project site drainage area, which is relatively small (WSDOT 2011). The project site crossing has been evaluated and determined to be a low risk site based on the Climate Impacts Vulnerability Assessment maps (Figure 61). Based on the determination of this location being a low risk

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site, no additional climate change design modifications were made. The new structures were designed so their foundations do not become exposed during the 500-year flow event. Also, hydraulic modeling indicated that the flow through the replacement culvert is not predicted to become pressurized (i.e., no freeboard) during the 500-year event.

7.1 Climate Resilience Tools

WSDOT also evaluates crossings using the mean percent change in 100-year flood flows from the WDFW Future Projections for Climate-Adapted Culvert Design program. All sites consider the percent increase in peak flow estimated for 2080 throughout the design of the structure. Appendix I contains the information received from WDFW for this site.

7.2 Hydrology

For each design WSDOT uses the best available science for assessing site hydrology. The predicted flows are analyzed in the hydraulic model and compared to field and survey indicators, maintenance history, and any other available information. Hydraulic engineering judgment is used to compare model results to system characteristics; if there is significant variation, then the hydrology is reevaluated to determine whether adjustments need to be made, including adding standard error to the regression equation, basin changes in size or use, etc.

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In addition to using the best available science for current site hydrology, WSDOT is evaluating the structure at the 2080 predicted 100-year flow event to check for climate resilience. The design flow for the crossing is 203 cfs at the 100-year storm event. The projected increase for the 100-year event flow rate is 19.8 percent, yielding a projected 2080 flow rate of 243 cfs.

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7.3 Climate Resilience Summary

A minimum hydraulic opening of 24 feet allows for extreme event flows to pass through the replacement structure safely under the projected 2080 100-year flow event. This will help to ensure that the structure is resilient to climate change and the system is allowed to function naturally, including the passage of sediment, debris, and water in the future.

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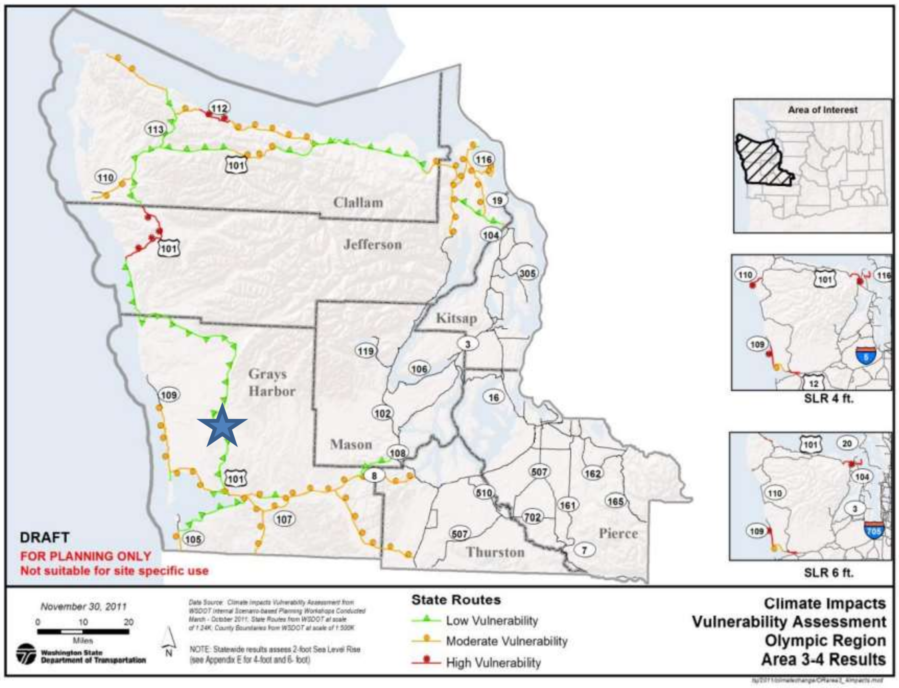

Figure 601: Climate impacts vulnerability assessment of Olympic Region areas 3 and 4 (source: WSDOT 2011). Site location is indicated by star

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8 Scour Analysis

Total scour will be computed during later phases of the project using the 100-year, 500-year, and projected 2080 100-year flow events. The structure will be designed to account for the potential scour at the projected 2080 100-year flow events. For this phase of the project, the risk for lateral migration and potential for degradation are evaluated on a conceptual level. This information is considered preliminary and is not to be taken as a final recommendation in either case.

8.1 Lateral Migration

Based on the evaluation in section 2.8.5, the risk for lateral migration of the project stream is considered small.

8.2 Long-term Aggradation/Degradation of the Riverbed

Based on the evaluation in section 2.8.4, there is a little risk of long-term aggradation at the project site over the life of the replacement structure. However, there is a potential risk of long term degradation at the site, with a worst case estimate of approximately 3 feet if the stream continues to incise and scour out embedded log grade controls between the crossing and a geologic control downstream.

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8.3 Local Scour

Three types of scour will be evaluated at this site: bend scour upstream and downstream of the replacement culvert, inlet scour, and contraction scour. Initial scoping level calculations indicate the amount of local scour will likely be small, on the order of 1-2 feet. These forms of scour will be evaluated in greater depth after the stream channel design has been finalized. It is anticipated that bend scour will be negligible at this site given the realignment that is proposed. Large wood pieces placed in the channel will have preformed scour holes constructed prior to rootwad placement.

Summary

Table 17 presents a summary of this PHD Report results.

Table 16: Report summary

Stream crossing category	Elements	Values	Report location
Habitat gain	Total length	11,266’	2.4 Site Description
Bankfull width	Average BFW	15’	2.8.2 Channel Geometry
	Reference reach found?	Y	2.8.1 Reference Reach Selection
Channel slope/ gradient	Existing crossing	1.25%	2.8.4 Vertical Channel Stability
	Reference reach	0.9%	2.8.2 Channel Geometry
	Proposed	0.89%	4.4.4 Channel Gradient
Countersink	Proposed	FHD	4.7.3 Freeboard
	Added for climate resilience	FHD	4.7.3 Freeboard
Scour	Analysis	FHD	8 Scour Analysis
	Streambank protection/stabilization	FHD	8 Scour Analysis
Channel geometry	Existing	Perpendicular	2.8.2 Channel Geometry
	Proposed	No Change	4.4.2 Channel Planform and Shape
Floodplain continuity	FEMA mapped floodplain	N	6 Floodplain Changes
	Lateral migration	N	2.8.5 Channel Migration
	Floodplain changes?	Y	6 Floodplain Changes
Freeboard	Proposed	2.0’	4.7.3 Freeboard
	Added for climate resilience	Y	4.7.3 Freeboard
	Additional recommended	0’	4.7.3 Freeboard
Maintenance clearance	Proposed	6’	4.7.3 Freeboard
Substrate	Existing	D_{50}=0.7”	2.8.3 Sediment
	Proposed	D_{50}=0.85”/1.5”	5.1 Bed Material
Hydraulic opening	Proposed	24’	4.7.2 Minimum Hydraulic Opening Width and Length
	Added for climate resilience	N	4.7.2 Minimum Hydraulic Opening Width and Length
Channel complexity	LWM	Y	5.2 Channel Complexity
	Meander bars	Y	4.4.2 Channel Planform and Shape
	Boulder clusters	Y	4.4.2 Channel Planform and Shape
	Mobile wood	N	5.2 Channel Complexity
Crossing length	Existing	111’	2.7.2 Existing Conditions
	Proposed	105’	4.7.2 Minimum Hydraulic Opening Width and Length
	Flood-prone width	43’	4.2 Existing Conditions Model Results

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Stream crossing category	Elements	Values	Report location
Floodplain utilization ratio	Average FUR upstream and downstream	2.6/3.1	4.2 Existing Conditions Model Results
Hydrology/design flows	Existing	See link	3 Hydrology and Peak Flow Estimates
	Climate resilience	See link	3 Hydrology and Peak Flow Estimates
Channel morphology	Existing	See link	2.8.2 Channel Geometry
	Proposed	See link	5.2 Channel Complexity
Channel degradation	Potential?	High	8.2 Long-term Aggradation/Degradation of the Riverbed
	Allowed?	Y	8.2 Long-term Aggradation/Degradation of the Riverbed
Structure type	Recommendation	N	4.7.1 Structure Type
	Type	N/A	4.7.1 Structure Type

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Appendices

Appendix A: FEMA Floodplain Map

Appendix B: Hydraulic Field Report Form

Appendix C: SRH-2D Model Results

Appendix D: Streambed Material Sizing Calculations

Appendix E: Stream Plan Sheets, Profile, Details

Appendix F: Scour Calculations (to be completed at FHD)

Appendix G: Manning's Calculations

Appendix H: Large Woody Material Calculations

Appendix I: Future Projections for Climate-Adapted Culvert Design

Appendix J: Co-Manager Comments on Draft PHD Report and Stream Team Responses

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